Eindhoven University of Technology

MASTER

# Condition-based maintenance optimization

## a condition-based maintenance policy for systems containing multiple non-identical components

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**Eindhoven, April 2012**

# Condition-Based Maintenance optimization

## A condition-based maintenance policy for systems containing multiple non-identical components

By

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**In partial fulfillment of the requirements for the degree of**

**Master of Science**

**in Operations Management and Logistics**

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# Abstract

This mater thesis provides a concept for the implementation of a Condition-Based Maintenance policy at Marel Stork Poultry Processing. An analysis is executed which identifies the possible implementation options of Condition-Based Maintenance at Marel Stork Poultry Processing. Furthermore, a Condition-Based Maintenance policy has been designed which is able to determine the optimal time of replacement for multi-component systems. Based on the scenario analysis, it is observed that the new proposed design can decrease the expected total maintenance costs considerable compared to the current maintenance policy used by Condition-Based Maintenance.

# Preface

This master thesis is the result of my graduation project at Marel Stork Poultry Processing in Boxmeer. With this master thesis I am not only finishing my master in Operaations Management & Logistics but also I have reached the end of my academic years. It has been a very nice experience and the added value of executing my master thesis at Marel Stork Poultry Processing has been unforgettable.

First of all I would like to thank to people you have motivated and supported me during my master thesis. These are; Dr. Tarkan Tan from the Technical University of Eindhoven and Jan Melssen form Marel Stork Poultry Processing. Their patience, motivating support and inspirational discussions provided me with the helping hand which I needed at some times. The master thesis was a though journey at times as the topic was quite new for all parties. Nevertheless, their support and criticism at times confronted me with aspects in project management which I still have much to learn. This is something I will take with me as I make the next step from academics to the working life. Secondly, I would like to thank Professor Geert-Jan van Houtum for his participation and that he provided me with the opportunity to participate in the ProSeLo project.

At Marel Stork Poultry Processing I would like to thank all my other colleagues in the SG CTS department for their support and warm welcome.

I would like to thank my always supporting family. My dear mother for her support at all times. There are no words that can describe my gratitude. My father for being an inspiration and his everlasting dedication and my siblings for their continuous encouragement. I would like to thank my uncle who always took interest in my studies. Finally, I would like to mention my gratitude to my friends at the university Otman and Umberto, during my years at the university they have been a great support as well as Ronald, Rik and Xiao with whom I enjoyed working with during the courses.

Sherif Hussein,

April 2012

# Executive Summary

This report is the result of a master thesis at Marel Stork Poultry Processing. The main activity of Marel Stork Poultry Processing is the design and production of production lines for poultry processing. Besides their main activities they provide service for the maintenance of these industrial systems.

An important part of the after-sales service and of being a good service provider is having a good maintenance concept. In the optimization of maintenance one of the latest phenomena is Condition-Based Maintenance. Therefore this project aims to find solutions to implement Condition-Based Maintenance and how the maintenance planning can be made based on this maintenance concept from an Original Equipment Manufacturer point of view.

The project consists of two stages, namely, diagnostics and design. In the diagnosis stage, the current situation for the maintenance is described in detail to identify all possible problems and opportunities. After defining the current gaps within the current preventive maintenance approach and opportunities to where predictive and condition based maintenance could contribute, a design to include condition based maintenance in the current preventive maintenance strategy is developed.

In the diagnostics phase, interviews are conducted and the current set-up and classification of spare parts are analyzed. Furthermore, the current practice and execution of maintenance activities are analyzed and it is evaluated how Condition-Based Maintenance can be integrated. As a result of the diagnostics phase, the project is clearly formulated and the possible application of condition monitoring and the value of its application per spare part types are clearly identified. The overall maintenance (service) concept used can be divided in four main elements, namely service delivery, spare parts, maintenance kits, maintenance planning.

From a service delivery point of view the maintenance is delivered by the use of service visits by the Original Equipment Manufacturer. The service visits are generally executed at the customer in the weekends. During these service visits the maintenance activities are completed. This such that these maintenance activities can take place during a complete plant shutdown due to corporate regulations. Therefore, the maintenance planning is confronted with the constraint that it can only plan the maintenance activities once a week.

The second element is the spare part. The spare parts are classified into 5 categories. The categorization is based primarily based on two categories; the expected life time and its wearing process. The analysis concluded that one of the five spare parts are not suitable for Condition-Based

Maintenance, these are the consumables (“A” category). The following category (“B” category), are the spare parts which are critical in order to continue the production process. Despite of their criticality they currently follow a run-to-failure policy. These parts have been identified as suitable for Condition-Based Maintenance. Next are the spare parts which are subject to naturally and inevitable damage that occur as results of usage and of which the life time can be reasonable estimated. These are the so-called “C” and “D”, the distinction between the two is solely based on their expected life time. Their wear and tear characteristics make then suitable for the application of condition monitoring. The final spare part classification is a bit more complex to subject to condition monitoring. These are the so-called “E” classified parts. Currently, these parts are often prematurely replaced as result of decisions that are made by maintenance engineers. By subjecting these parts to condition monitoring the decision will not be solely made by an engineers opinion but be made by more advanced technological reasoning.

The third element is that of the maintenance kits. The maintenance kits are currently classified based on the time which they will be completed. Hence, a maintenance kit can include several different coded parts. To apply condition monitoring the current structure of the maintenance kits must be changed. The composition of the maintenance kits should not be determined based on the time of replacement of the parts but solely be determined based on the part coding. The final element is that of the maintenance planning. Currently, the above mentioned maintenance kits are scheduled by a block policy where the maintenance kits are scheduled to be executed every certain time interval.

From the analysis of the current maintenance (service) concept, it is seen that the “C” and “D” coded parts are approximately 80 % of the total parts which are included in the preventive maintenance schedules. Therefore, the focus of the project was how these parts given the above mentioned necessary changes could be included in a Condition-Based Maintenance concept and it is formulated as follows;

“*How can the preventive maintenance practices for a multiple component system include components subject to condition monitoring and therefore decrease the total life cycle cost, taking into consideration the economic dependence of the maintenance jobs?”*

Then in the design phase the pre-conditions, such that Condition-Based Maintenance can be implemented, are stated as well as a design which provides a method by which the preventive maintenance decision can be made with the use of information which is gathered by condition monitoring.

To implement Condition-Based Maintenance in a multi component environment several technical preconditions are necessary. Such as; each maintenance kit contain at least on trigger part which is seen as the critical component within that maintenance kit. It must be possible to detect a failure which prohibits the trigger part in question to perform its desired function by a soft fault. A soft fault is a fault which developed gradually with time. Furthermore, it must be possible to divide the, gradually in time evolving, fault into a “usefull” life and a “wear out” phase. The “wear out” phase is the phase in which it is able to technically indicate that a fault starts to occur. Finally, the time between the start of the “wear out” phase and the end of it must be larger than the time between the maintenance decision-making.

Several important aspects have been incorporated into the designed Condition-Based Maintenance planning method. Each maintenance kit has been assigned individual preventive as well as corrective maintenance costs. The preventive maintenance occurs if a maintenance kit is replaced prior to any failure, otherwise a corrective maintenance takes place. Furthermore, each time at least one maintenance kit is replaced a fixed costs is assigned. This shared fixed cost is assigned only once each maintenance visit independent of the number of maintenance kits replaced. The information gathered through condition monitoring is incorporated into the planning method such that each decision moment the individual expected costs of failure up to each possible replacement time is computed as well as the expected costs of the preventive maintenance.

After determining the new planning design, a calculation model is constructed to evaluate the performance of the new design compared to the current maintenance policy, a policy which does not take clustering of maintenance activities into account and a final policy which takes clusters the maintenance activities but does not take any condition monitoring information into account.

It is concluded that the new proposed maintenance design outperforms the current maintenance policy as well as the maintenance policy which does not make use of any clustering in all cases. The relative performance of the Condition-Based Maintenance policy, regarding the expected total costs, seemed to increase when the costs of an unexpected failure increased. In the same case the effect of the individual reliability failure threshold (which determines the individual maximum replacement time) becomes less influential. Furthermore, the shape of the updated remaining useful life distribution has a significant influence on the performance of the Condition-Based Maintenance policy.

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# 1. Introduction

Advanced technical systems, also named advanced capital goods (e.g., slaughtery equipment, MRI scans, material handling systems) are often used in critical parts of the processes of the end-users. Keeping these systems up in the field (availability) is crucial since operations of the users may halt due to failures of these systems, thereby leading to significant losses. Due to the technical complexity of these systems, the users are more and more asking for after-sales service from the Original Equipment Manufacturers (OEM). This is not yet presently the case at Marel Stork Poultry Processing (MSPP) although MSPPs philosophy is going in the same direction, step by step. Currently, MSPP does not make use of strict performance related (e.g., 98% uptime) Service Level Agreements (SLAs) but sells their systems in the traditional way and then provides service to the customer charging this separately. Nevertheless, MSPP is eager to improve in this aspect and preparing itself for when the time comes to move up in the service provider continuum (Oliva and Kallenberg, 2003).

An important part of the after-sales service and of being a good service provider is having a good maintenance concept. If MSPP wants to move upwards on the service continuum and be able to provide SLA's and therefore increase their revenue, the maintenance tasks must be optimized. In the optimization of maintenance the new phenomena is Condition-Based Maintenance (CBM). The current situation at MSPP is such that very little data is stored for maintenance purposes because it is not known what to store. As first step into the world of CBM, Stork wants to set up a program where they use condition monitoring information to further optimize their maintenance scheduling. Hence, this master thesis aims to provide MSPP with a roadmap in which it is made clear how condition based information can be used to optimize their maintenance scheduling.

## 1.1. Company Description

The history of MSPP starts in January 2009 when Marel Food Systems acquires Stork Food Systems. Before this time Marel Food Systems and Stork Food Systems where both OEM's but where the focus of Stork Food Systems lay in the poultry industry, Marel Food Systems was more active in the fish and red meat sectors. Combined, the yearly turnover is estimated to be 660 million euros with more than 4000 employees.

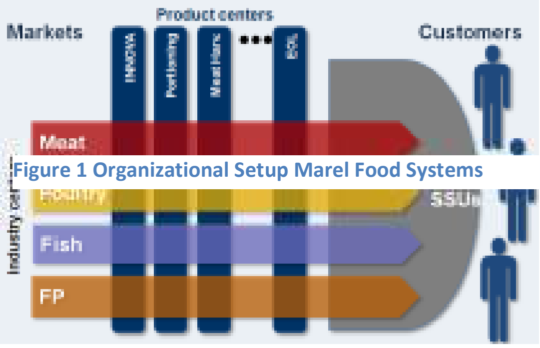


Figure 1 Organizational Setup Marel Food Systems

Together, the companies expect to improve the integration of solutions within the food sector. The future integrated organizational setup is given in Figure 1.

The history of the company that was named Stork Food Systems up to 2009 starts in 1835 when the thirteen-year-old Charles Theodorus Stork started a textile factory. Due to competition within this sector, the company started focusing on the production of industrial products like steam machines. In 1930 the company became a conglomerate, which produced several not related products like cranes, sea tugs, and production machines for the food industry. Despite bad results in the sixties, several acquisitions took place, one of them (in 1963) the acquisition of 'Wiericke', a producer of machinery used for the slaughtery of poultry. Due to automation, the poultry sector was rapidly expanding, and in 1975 the independent subsidiary Stork PMT (Poultry processing Machinery and Technology) in Boxmeer (The Netherlands) was established. Stork PMT expanded activities in 1976 to Gainesville (USA) where 'Gainesville Machine Corporation' was taken over and renamed Stork Gamco, which nowadays is the most important poultry processing equipment supplier in the USA. In 1988 Stork saw the trend of convenience food and acquired Titan, which produced machines for meatball production. Nowadays, Titan, also located in Boxmeer and Gainesville, is specialized in developing machines for the further processing of poultry, red meat, potato, and fish into semi finished, convenience food and meal component items. With this acquisition, Stork PMT became able to deliver full line solutions. In 2006 Stork PMT acquired Townsend, located in Iowa (USA) and Oss (The Netherlands) and named it Stork Townsend. Stork Townsend develops and produces specialized equipment for the pork and beef processing industry.

Currently, Stork PMT also produces poultry machinery in Dongen (The Netherlands) and Piracicaba (Brazil). The facility in Piracicaba is named Stork Food systems LTDA. Due to the several locations of the production facilities, the risk of not being able to deliver (spare) parts to customers, due to unforeseen accidents (e.g. fire) at production facilities is reduced. This may be an important factor for customers whose costs dramatically increase when production is idle. Finally, Stork Food Systems BV is the name of all the international sales and service offices under the Food Systems group.

## 1.2. Poultry Processing

With the acquisition of Stork Food Systems by Marel Food Systems, the concern can deliver full line solutions for the poultry as well as the fresh meat industry. Since the poultry process is the core business for the Boxmeer location, this process will be further elaborated.

The poultry processing process can be categorized as a production line. This production line is a semi-automatic line where the birds are guided through the process by a logistic system. Hence, birds are processed while they move (mostly suspended on shackles) through a line. These production lines can range from 2 up to 6 kilometer long in chains used for the logistical system. The extensiveness of the production line depends on which state the bird must be as final product and the production requirements. Appendix A shows a poultry processing line which includes all the possible phases. The production line can diver not only on length but subsequently it can also diver on the types of handlings which are executed by the automated line. A fully automated and equipped poultry process can exist of the following processes; Supply line, Stunning, Scalding, Plucking, Evisceration, Harvesting, Chilling, Weighing, Portioning, Deboning, Packaging and finally a Storage.

## 1.3. Machinery supplied by Marel Stork Poultry Processing

The corporate sales strategy of MSPP is to provide clients with an integral solution for their client's poultry plants. These plants can vary in size and depth of processing. Some plants are designed to be able to handle the whole poultry process described above, whereas other smaller plants only process the chickens up to carcasses ready for consumption. For commercial reasons MSPP decomposes a clients plant into one or more production lines. A production line is a sequence of several different process lines after each other. Hence, the process line is a small part of the production line which executes a precise process. Process lines are lines where several sales units are aligned into a workable sequence to execute a functional activity, such as cooling process, supply process, plucking process or the deboning process etc.

The whole decomposition of a poultry plant is shown in Figure 2. The sales unit is a standard machine that is sold to the customer. The sales unit itself exists out of several assemblies which are denoted as legends. Hence, legends are sub-assemblies of a machine and they can be composed of other legends or articles as shown in Figure 2. An article is a loose part such as a bolt or a special cut plate. These articles can either be purchased by an external supplier or be crafted out of raw materials by MSPP themselves. Steel plates are steel pipes that need to be crafted into the right measurements are examples of raw materials.

In summary, the sales unit (which is regarded as the machine level) is the highest level for which MSPP provides customers with concrete machines. MSPP also provides solutions for connecting the different sales units together although these connecters exist out of legends. Further, the article level is regarded as the part level. Subsequently, any item between the sales unit (machine level) and article (part level) is called a legend. Hence, all assemblies and sub-assemblies of a machine are considered as legends if it is not the lowest level.

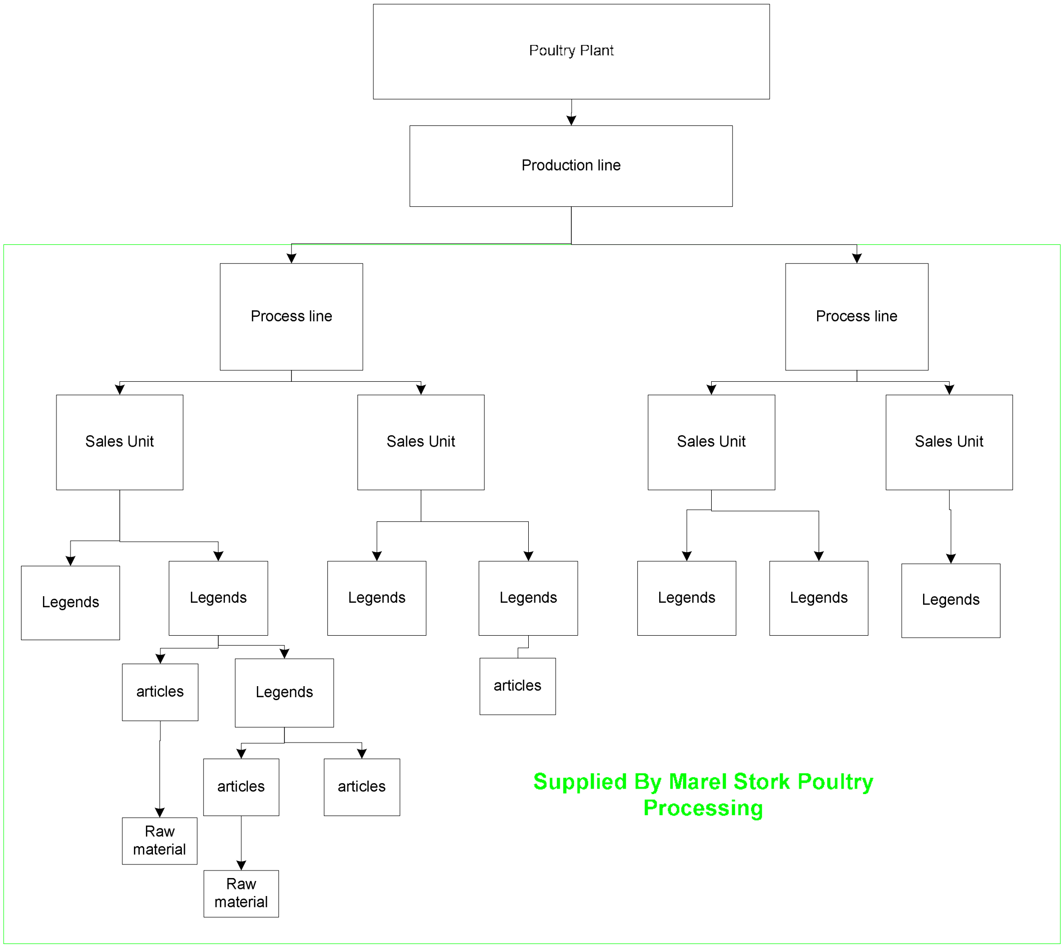


Figure 2 Structure poultry process

## 1.4. Initial project formulation

Marel Stork Poultry Processing wants to respond to the customers asking for more service support. Customers are becoming more demanding due to professionalization and industrialization process which the poultry industry is experiencing. As result fewer systems provided by MSPP are ordered by small plants and there are an increasing number of large professional slaughter production facilities. This is affecting the way MSPP has to conduct their business in general. The industrialization and professionalization of the poultry industry has as affect that the customers are leaning more towards their own area of expertise and are expecting MSPP to provide a larger role as service provider, instead of only manufacturer of capital goods. This is in line with the theory suggested by Olivia and Kallenberg (2003) in which they suggest that in the current times as well as the future, services are becoming more and more important for the clients of OEM's. In addition they suggest that it is the service that distinguishes a good manufacturer from the bad.

To anticipate the above situation, MSPP is conducting several internal projects to improve the companies infrastructure regarding aspects that are related to them being able to make the switch from manufacturer to service provider. In the sense of selling complete solutions regarding poultry slaughter processes. Subsequently, MSPP is searching for solutions to further develop their maintenance department and maintenance activities from mainly time-based maintenance activities towards more sophisticated CBM methods.

Therefore, the project can be formulated initially as follows:

"*How can Marel Stork Poultry Processing use a condition based maintenance program to further optimize their preventive maintenance service?"*

The project is divided into two stages, diagnosis and design. In the diagnosis stage, the current situation for the maintenance is described in detail to identify all possible problems and opportunities. After defining the current gaps within the current preventive maintenance approach and opportunities to where predictive and condition based maintenance could contribute, a design to include condition based maintenance in the current preventive maintenance strategy is developed.

## 1.5. Structure of the report

The report is divided in several chapters. First chapter 1 serves as an introduction and discusses the company and its market environment. Chapter 2 provides a more detailed overview of the current maintenance services provided by Marel Stork Poultry Processing. Chapter 3 discusses the research environment and the research questions. After which Chapter 4 will provide a literary overview regarding condition-based maintenance. Chapter 5 will go on and will describe the designed maintenance policy and its optimization model. Chapter 6 and 7 will discuss the case study and its results based on several different scenarios. Furthermore, Chapter 6 will describe how the scenarios are executed. In Chapter 8 the conclusion will be presented followed by the recommendations in Chapter 9.

# 2. Project environment & definition.

Introduced paragraph 1.4 is that MSPPs goal is to improve their preventive maintenance services by implementing a condition-based maintenance program. In order to decide how such a program can have an added value the current service delivery provided by MSPP is described. Paragraphs 2.1 up to 2.5 describe all facets of the current infrastructure relating to MSPP maintenance handling. Paragraph 2.5 provides a short summary of the possibilities concerning the implementation of condition based maintenance. Based on the possibly implementation options Paragraph 2.6 and 2.7 describe the problem formulation addressed in the project and the associated project scope.

## 2.1. Service delivery Marel Stork Poultry Processing

Service visits are the most common service activity that MSPP provides to its customers. These visits are generally executed at the customer in the weekends. In a typical visit, the mechanics perform the preventive maintenance activities. These maintenance activities are almost always executed during a complete plant shutdown due to corporate regulations. These complete shutdowns are called overhauls and will be discussed further on in this chapter. The larger professionalized poultry production plants impose these regulations on themselves to assure the efficiency of the maintenance activities, safety and a clean environment for hygiene reasons. In general one service engineer is able to execute all necessary handlings which are needed for preventive maintenance, no specialists are required.

## 2.2. Service Parts

For the service parts MSPP has developed a coding design. MSPP uses a so-called ABCDE classification for the service parts. The as “E” coded parts are parts that are condition-dependent and are replaced according to a certain visual condition criteria. These visual inspections regarding the condition of the E parts are executed during the scheduled maintenance visit. What further makes E parts important for this research is that they are on their own capital-intensive parts. They are parts that are so capital-intensive that it is not responsible to just replace them based on a time or count criteria. Furthermore, the E parts are parts that usually have a large impact on the yield of the system. A drawback of the E parts as visual inspected parts is that they are often prematurely replaced, which considering that they are capital intensive parts increases the Life Cycle Costs of the system significantly. The E parts are often prematurely replaced because the mechanics do not like the responsibility of having to make this decision. When confronted with the decision concerning the E parts mechanics rather prefer to be “safe than sorry”. Therefore they often replace this capital intensive part although its lifetime is not completely used. This means over the lifetime of the machines the life cycle cost increase due to the fact that more spare parts are used then necessary.

The “C” and “D” parts are both parts that are subject to wear and tear. Hence, these parts are subject to naturally and inevitable damage that occur as a result of usage. The distinction between the C and D parts is that the C parts currently follow a scheduling program in which they are replaced at least every two years and at most two times per year to assure correct working. These are also called small overhaul parts. D parts are classified differently than C parts because their wear process is less intensive compared to that of the C parts. D parts are replaced every 3 to 5 years depending on the operating conditions and rates to which the part is exposed to. Finally, the D parts are so-called major overhaul parts and hence are less likely to wear out. Currently, there is the belief in the maintenance department that the life time predictions of these parts are very safe. This means that the life time estimations used are the shortest life times which can be expected.

“A” parts are so-called consumables and are by definition easy accessible. These are parts that make contact with the product to be processed and have a direct effect on the technological action of the machine. It are parts which must be replaced on a frequent basis. The A parts are often not capital intensive. Furthermore the need of frequent replacement and the predictability of the failure pattern of the A parts has provided MSPP and the customers the opportunity to have optimized the preventive maintenance pattern of these parts. Therefore these parts are not very suitable for condition monitoring. “B” parts are repairable parts that must be replaced at time of failure in order to continue the production process. These are parts or assemblies of parts, which, if defective, make it difficult or impossible for production to continue. Hence, these parts are the major causes of unscheduled downtime. Especially because the policy for these components is run-to-failure, even when considering that they are crucial for the process.

Finally, it can be concluded that MSPP has not found a practical and / or good solution for the B and to a lesser extent the E parts. For MSPP to feel more secure such that it can provide their clients with SLA’s the introduction of CBM techniques can be introduced regarding these parts. This is to be able to provide certain uptime guarantees with more certainty and decrease the total life time cost by not prematurely replacing the E parts. Regarding the C and D parts the premature replacement costs are the expected unnecessary incurred costs. These costs can be very substantial, as the C and D parts represent approximately 85% to 90% of the coded parts within the machines. The substantial premature replacement cost for C and D parts is due to the extremely safe life time estimations. In further analysis the A parts will be left out of scope. These parts are very frequently replaced by the customers themselves.

## 2.3. Maintenance kits

The maintenance is done at the customer during overhauls at predetermined moments. According to MSPP the service parts coding allows them to compose several kits which can be used during the overhauls. These kits used during the overhauls are called maintenance kits. There are three different kinds of kits that are used during the overhauls; small, major and total maintenance kits kits. The small maintenance kit contains the C service parts. This means when a small overhaul is planned it is known with certainty that the C parts are replaced. Besides the C parts the small maintenance kit contains E parts. As described previously the E parts are condition-dependent and are included into the maintenance kit as an inspection related item. Every time an overhaul is carried out the parts classified as E parts are visually inspected and then based on the judgement of the mechanic a replacement decision is made.

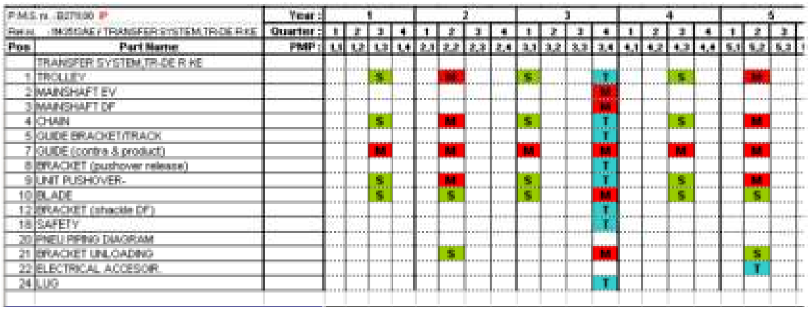
Next is the major maintenance kit which contains the C parts as well as the D parts. Additionally, as with the small kit, it may be possible that some of the E parts are replaced. The major overhauls are executed on a less frequent basis than the small overhauls as the D parts have a longer lifetime than the C parts. The major overhaul parts in general do not have a high replacement cost but if failed or their performance decreases it does have an effect on the performance of the system. Finally, there is the total maintenance kit. The total maintenance kit contains all C, D and E parts. Hence, in the total overhaul activities the E parts do not have to be inspected by the mechanics but they have already been included with certainty in the maintenance kit.

As introduced before MSPP provides its customers with a preventive maintenance scheme in which the above defined maintenance kits are planned. Hence, the time of the maintenance is decided according to the preventive maintenance scheme provided by MSPP. Nevertheless, the exact time is determined in an agreement with the client and MSPP. The maintenance is generally planned for in the weekend rather than a weekday. On average a client works five and a half days per week and 16 production hours per day. The remaining available hours on these working days are needed for cleaning procedures which are rather strict in the European region due to hygiene related laws. Hence, the overhauls usually start on Saturday. The necessary parts (C, D, or E) are replaced depending on the type of overhaul (small, major or total). Then the mechanics focus on installing the necessary settings. If the overhauls cannot be completed on Saturday, the employees continue to work on Sunday. Finally, it is clear that only the C, D and E parts are included in the preventive maintenance schemes.

## 2.4. Preventive Maintenance Schemes

Previously mentioned is that MSPP prepares preventive maintenance schemes for every machine sold to their customers. This is a service that is necessary due to MSPP's high knowledge regarding the failure times of parts when operating in a production line. The preventive maintenance schedule shows the overhaul work to expect for a specific machine structure (its parts) in order to keep it in good mechanical condition. These schemes are prepared according to the working rate of each client's process. In general, these exist three types of maintenance schemes, **less preventive (-2P), preventive (P)** and **more preventive (2P)**. Less preventive schemes are suitable for plants which are subject to low working rates, more preventive schemes are necessary and more suitable for plants that work for instance 2-3 shifts a day.

The preventive maintenance schemes that are developed for the sales units sold to the customers can differ in two aspects of each other. They can differ of each other due to the frequency that an overhaul is required and the sequence of the different maintenance kits when an overhaul is scheduled. Regarding the frequency of the scheduled overhauls the preventive maintenance schemes can differ of each other as for some sales units scheduled overhauls are executed every year, whereas for other sales units the scheduled overhauls can have a time interval of every 6 months. Furthermore, the sequence of the types of overhauls can also differ. For example, it could be that for a certain assembly the preventive and more preventive sequence is "Small – Small-Major-Small –Small –Total", while the less preventive ones have the sequence "Small-Major-Small-Total". Figure 3 shows an example of a preventive maintenance scheme of a sales unit (machine).



| P.M.S. nr. : [illegible] | | Year : | 1 | | | | 2 | | | | 3 | | | | 4 | | | | 5 | | |
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| | TRANSFER SYSTEM TR-DE R.KE | | | | | | | | | | | | | | | | | | | | |
| 1 | TROLLEY | | | | S | | | M | | | S | | | T | | | S | | | M | |
| 2 | MAINSHAFT EV | | | | | | | | | | | | | M | | | | | | | |
| 3 | MAINSHAFT DF | | | | | | | | | | | | | M | | | | | | | |
| 4 | CHAIN | | | | S | | | M | | | S | | | T | | | S | | | M | |
| 5 | GUIDE BRACKET/TRACK | | | | | | | | | | | | | T | | | | | | | |
| 7 | GUIDE (contra & product) | | | | M | | | M | | | M | | | M | | | M | | | M | |
| 8 | BRACKET (pushover release) | | | | | | | | | | | | | T | | | | | | | |
| 9 | UNIT PUSHOVER- | | | | S | | | M | | | S | | | T | | | S | | | M | |
| 10 | BLADE | | | | S | | | S | | | S | | | M | | | S | | | S | |
| 12 | BRACKET (shackle DF) | | | | | | | | | | | | | T | | | | | | | |
| 18 | SAFETY | | | | | | | | | | | | | T | | | | | | | |
| 20 | PNEU PIPING DIAGRAM | | | | | | | | | | | | | | | | | | | | |
| 21 | BRACKET UNLOADING | | | | | | | S | | | | | | M | | | | | | S | |
| 22 | ELECTRICAL ACCESOIR | | | | | | | | | | | | | | | | | | | T | |
| 24 | LUG | | | | | | | | | | | | | T | | | | | | | |

Figure 3 Standard Preventive Maintenance scheme for a Sales Unit

It is previously mentioned that the preventive maintenance schemes shown in Figure 3 only contain the A, C, D and E parts. How E parts can benefit from condition monitoring has also been discussed as well as how the A parts are primarily not interesting for condition monitoring. Left are the C and D parts. In general the C and D parts could be of interest when considering condition monitoring. The first idea is to subject the C and D parts to condition monitoring such that the maintenance kits (small, major, total) could be optimized. Hence, given the above preventive maintenance scheme how to optimize the time of the overhaul such that all maintenance kits are executed in the same weekend?

Currently, the small overhaul is determined based on the C parts and therefore the fixed overhaul interval time is also determined by the C parts. Then the D parts are clustered in the most delayed overhaul for which the maintenance department, based on experience, knows that the D part will reach without failing or causing performance loss. Hence, the maintenance scheme is constructed very safe. Therefore the opportunity of improvement is mostly on extending the usage time of the part rather than reducing downtime due to unexpected failure.

Finally, there is one more complexity hidden in the current preventive maintenance schema. In some situations the preventive maintenance also assigns interdependencies between two or more sub-assemblies. This interdependency means that if either one of these sub-assemblies is replaced it is better to replace the other one simultaneously. These interdependencies are mostly based on a mechanical reasoning. These interdependencies make the optimization of the current preventive maintenance schedule more complex. This because they cause an additional constraint, which is that if either one of the sub-assemblies fails the other sub-assembly also must be replaced. This can be avoided by assuming that one of the assemblies always has a longer life time then the other.

## 2.5. Possible implementation scenarios condition based maintenance

This chapter has described the current maintenance handling with the main subject the overhauls with its related elements. Given the current structure within the component classification and preventive maintenance schemes three conclusions regarding the possibilities of condition monitoring can be drawn. The conclusions are:

- The currently used preventive maintenance practice, which makes use of periodic overhauls, includes the C, D and E parts. The current preventive maintenance structure leaves out parts which are critical in order to continue the production process. These are the so-called B parts. These are parts for which the maintenance team has not felt confident enough to predict its lifetime purely based on experience. Examples are; motor reductors, three phase mortars, chains, gearboxes, pneumatic parts such as valves and critical hydraulic parts. Without going into too much technical detail it can generally be said that these are parts that are appropriate for the use of condition monitoring.

  Concluding that, the use of condition monitoring information as substitution of the run-to-failure policy for the B parts can increase the utilization of the customer's process. Furthermore, the current run-to-failure policy forces the client to always have a spare part on inventory. Hence, the introduction of condition monitoring increases the failure predictability and therefore the inventory control. It decreases the inventory costs which are assigned to the spare parts as the inventory control can be connected with the residual life distributions.

- The current preventive maintenance practices include so-called E parts which are parts subject to a so-called visual inspection. These visual inspections only take place during the scheduled overhaul visits. The so-called E parts, depending on which E part, do not cause major downtime but are very capital intensive parts. These parts are often replaced prematurely which increases the cost over the lifecycle of the machine. Needless to say, condition monitoring can be used as a solution such that the decision of replacement is not taken by the mechanics but is based on accurate condition information. Hence, decreasing the contribution of these parts to the total life cycle cost of the machine. The introduction of condition monitoring furthermore increases the manageability of the logistics regarding the goodsflow of these parts. This partially decreases the logistic costs.
- The currently classified C and D parts are the main contributors of actions within the current preventive maintenance schemes. They are the third possibility when considering the application of condition monitoring to decrease the life cycle costs. These parts are scheduled, in the maintenance kits small, major and total, in a very preventive manner. Hence, they are scheduled in a very safe way and therefore mostly not used to their full potential life time. This is because they are often not very expensive parts but are required to be replaced rather frequently. They might not be expensive parts individually but they are often parts which occur frequently in a machine. Although in different sub-assemblies which means that measuring one of these parts does not say anything about the other.

Condition monitoring can be used as a solution to the currently very safe timed preventive maintenance schema. Therefore extending the usage of the parts and prevent premature replacement. This by decreasing the life cycle costs by decreasing the number of components used during the life cycle of the machines. Additionally, condition monitoring and steering the preventive maintenance schemes by condition monitoring information decreases the current subjectivity of the schemes. The preventive maintenance schemes are currently determined by a few “experts” and are totally based on their interpretation.

When striving to optimize the maintenance scheduling of the C and D parts through the optimization of the execution time of the maintenance packages small, major and total two complexities arise. First, a sub-assembly can contain C and D parts and therefore be subject to a small as well as a major overhaul. If the C part which is in both maintenance kits is the performance indicator we must assume that the C part is also representative for the D parts. This can complicate things because the D parts have a much longer life time. Secondly, there is the existence of the dependence between sub-assemblies. This dependence is caused by the mechanical layout. The dependence indicates that due to the mechanical structure it is more practical to replace both sub-assemblies if one of the assemblies must be replaced. Hence, an additional constraint, which is that if either one of the sub-assemblies fails the other sub-assembly also must be replaced exists.

This part ends the analysis and diagnosis stage of the project. We can summarize that the three possibilities of subjecting condition monitoring are twice to decrease the life cycle cost by decreasing the probability of premature replacement and once by increasing the utilization level of the process.

## 2.6. Project formulation

According to the current problem and suggested remedy, the research assignment which was used as guide during the project can be formulated as follows:

*"How can the preventive maintenance practices for a multiple component system include components subject to condition monitoring and therefore decrease the total life cycle cost, taking into consideration the economic dependence of the maintenance jobs?"*

The research assignment raises the following sub-questions:

- *How can the decision be made if it is suitable to determine the replacement time of a maintenance job through a condition-based maintenance policy?*

Academic journals subscribe a large amount of methods to make use of condition monitoring information. To give more perspective in this wide range of possibilities a classification of the preconditions, necessary to be able to implement condition based maintenance, is presented.

- *How can the components which are subject to condition monitoring be clustered with the components which are not, given the constraint of having overhaul visits?*

Parts that are subject to condition monitoring are only a small fraction of the total amount of parts which should be included in the preventive maintenance practice during the overhauls at the customers. To be able to optimize the execution time of the overhauls they can be directed by a few elementary parts which then determine the time of execution for the overhaul.

- *How should the maintenance plan incorporate restrictions regarding the planning horizon of the maintenance activities?*

Furthermore, the length of the planning horizon must be taken into account. The effect of the length of the planning horizon on the maintenance plan and how long a planning horizon should be taken when using condition monitoring techniques must be researched. This issue leads to the above mentioned sub-question.

- *How does the introduction of condition monitoring for a selected number of components into the maintenance practices influence life cycle cost of a system?*

Finally, when the above research questions have been answered and the maintenance plan has been developed a business case will be provided for a part of the systems used by MSPP to provide insights regarding the possible savings of the new maintenance plan and the corresponding methodology. The effects should be shown on the total life cycle cost of the system.

## 2.7. Project Scope

Previously discussed is that for this research MSPP is chosen as the company to study in this project. Although MSPP has customers worldwide, only the more advance and larger customers within the Western European region are taken into account. Especially customers for which the whole plant exist of MSPP machines and equipment or customers who at least purchased and installed whole process lines by MSPP. The reason for this is that these customers in general demand and set the highest standards for machine availability and efficient use of machines. Furthermore labor is relatively expensive in the Western Europe region compared to other parts of the work which makes unexpected downtime significantly more expensive.

The analysis identified the B, E (condition dependent) and C &D parts as parts for which there are demonstrable business reasons to subject them to condition monitoring. This project will focus on the C and D parts by the optimization of the execution time of the different overhauls. The project will focus on how the planning can be optimized by subjecting several C or D parts to condition monitoring and therefore create a dynamic overhaul scheduling scheme. The choice to focus on the C and D parts is because the analysis pointed out that these parts account for about 85% to 90% of the coded parts. Due to the current subjective manner of planning all these parts are replaced in a rather safe way and therefore increase the life cycle costs significantly.

The project will focus on two subjects. First the project will discuss how can be determined if a maintenance kit is suitable to subject to condition monitoring. Regarding the first subject a roadmap will describe which will discuss the relevant factors which must be taken into consideration such that it is able to decide if a maintenance kit is worth investing in to implement condition monitoring tools. Secondly, the project will provide a decision support system to decide when the scheduled overhaul should be executed. The decision support tool should decide which maintenance kits should be clustered together and at which time the overhaul should take place. Due to lack of available data regarding the degradation of the parts that are part of the project, the testing of the decision support tool will be done with simulated lifetime data of several recognized life time distributions. The workable decision support tool for the overhaul packages will assume that for several sub-assemblies residual life time data is available whereas in reality this is not the case. This data will be generated through a simulation. Furthermore the current structure of the overhaul scheme is considered and is taken as a given. This concludes that the current overhaul packages and schemes can be seen as a constraint and cannot be adjusted. Hence, the decision support tool will optimize the current overhaul schemes assuming that for several sub-assemblies residual life prediction data is available.

During the project a test case will be executed on one of the sales units, namely, the transfer system which transfers the chicken carcass from the evisceration phase to the cooling system where the carcasses are chilled. The decision is made to choose this sales unit as test case is because it is a critical machine for which downtime has drastic consequences for the whole process of the plant. Furthermore the sales unit contains several critical B parts. However with the design and decision support model developed, it will be possible to do the same on other sales units provided that the necessary input values specific to that sales unit are entered.

# 3. Preconditions implementation Condition based maintenance

Planning preventive maintenance actions by the use of a condition based maintenance program is a complex subject. The complexity lies not only in the creation of a planning policy but in the fact that to be able to extract the necessary information from a system several technical aspects must also be satisfied. Therefore, it is not always feasible to implement CBM. The existing literature describes these issues under the name "maintenance decision making". The decisions that are made in these maintenance decision models can be described as preconditions. This chapter will describe the preconditions necessary for MSPP when implementing condition based maintenance to plan the execution time of the maintenance kits. First, Paragraph 4.1 provides a short overview of the current existing literature related to the maintenance decision making models. After which Paragraph 4.2 determines the preconditions. The stated preconditions in Paragraph 4.2 are all extracted from existing literature regarding CBM or condition monitoring.

## 4.1 Literature review: Maintenance decision making models

The decision making process of CBM is a broad and extensive task. It mainly covers two important tasks; at first which component to subject to condition monitoring; and, secondly is this component suitable to subject to condition monitoring. The majority of the academic literature describes manners how to identify which component should be subjected to condition monitoring, how the condition information can be gathered and finally how the gathered data can be manipulated in a meaningful manner. The decision when to use CBM can be categorized as a maintenance tactics selection. Selcik and Aven (2011), Moubray (1997), Labib (2004), Waeyenbergh and Pintelon (2009) and Khalil et al. (2005) all propose different decision frameworks to decide which kind of maintenance concept should be used. In all these decision frameworks one or more questions are asked which then lead to the decision if CBM through continuous condition monitoring should be used as a maintenance policy.

The model of Selcik and Aven (2011) base their decision to use CBM in the form of condition monitoring solely on the question if continuous monitoring is feasible. Furthermore, Labib (2004) designed a decision matrix based on the mean time to failure (MTTF) and mean time between failures (MTBF). Hence, the decision matrix proposed by Labib (2004) is based on the identification and quantitative ranking of components regarding its cause of downtime and there frequency of failures. The matrix then proposes different maintenance policies based on their location in the matrix. Although Labib's (2004) method can make use of quantitative measures, the cut-off points within the matrix lack (precise) quantitative guidelines which make them of an arbitrary kind. Finally, according to the matrix proposed by Labib (2004) components which have a low frequency of occurring but a high downtime should be subjected to CBM. The same as Labib (2004), Khalil et al. (2005) has developed a dual criteria categorization grid. The criteria consist of: the ‘failure frequency’ and ‘cost of failure’. Khalil (2005) is the first that integrates the assumption that the best way of reflecting the consequences of a failure is by estimating the financial losses. For this Khalil (2005) has developed a cost function of failure. Disappointing is that Khalil (2005) neglects the question of how can CBM benefit the company when implementing it.

The decision process proposed by Waeyenbergh and Pintelon (2009) is by far the most extensive method compared to the other reviewed methods. Waeyenbergh and Pintelon (2009) try to integrate all relevant aspects of maintenance decision making in an easy accessible method. Just as within the other decision models, Waeyenbergh and Pintelon (2009) do not only provide CBM as a possible maintenance solution. Some of the questions (decision notes) in the decision scheme are rather superficial and lack the depth and information needed to be able to answer them. Questions such as: “Is technical condition measurable?” and “Are the expected cost / benefit of CBM acceptable?” The first question is directed to the technical side of CBM, but Waeyenbergh and Pintelon (2009) do not mention when a technical condition is measurable. Furthermore, the same can be said for the second question which is economic of nature. For this question Waeyenbergh and Pintelon (2009) provide no information in how to define if the expected costs / benefits of CBM are acceptable.

Concluding that the majority of the available maintenance decision methods base their decision either on several technical based questions and very few try to integrate the economical viewpoints in the decision methods. Technical questions such as; “Is technical condition measurable?” or “Are CM tools available?” or even in the broadest sense “Is continuous monitoring feasible?” are most common. The economical effect of implementing CBM is a rather untouched item within the literature. Only one article mentioned that the expected benefits and costs should be taken into account. Unfortunately, that was the only thing mentioned on the topic living the readers with the questions, how to prove that.

## 4.2 Technical & Economical Preconditions

Most of the maintenance literature focuses on how to determine which component in a system should undergo which maintenance task. In this case the approach is slightly different. As mentioned previously in the report the maintenance replacement activity is done at the maintenance kit level. Hence, to assist in deciding if a maintenance kit should be subjected to a CBM strategy, the logic proposed by Jardine and Tsang (1995) in their proposed decision logic tree is used. This has resulted in the two main questions that must be answered shown in Figure 4. Figure 4 shows that to decide if a maintenance kit is appropriate for a CBM strategy there must be at least one part which satisfies a couple of technical requirements.

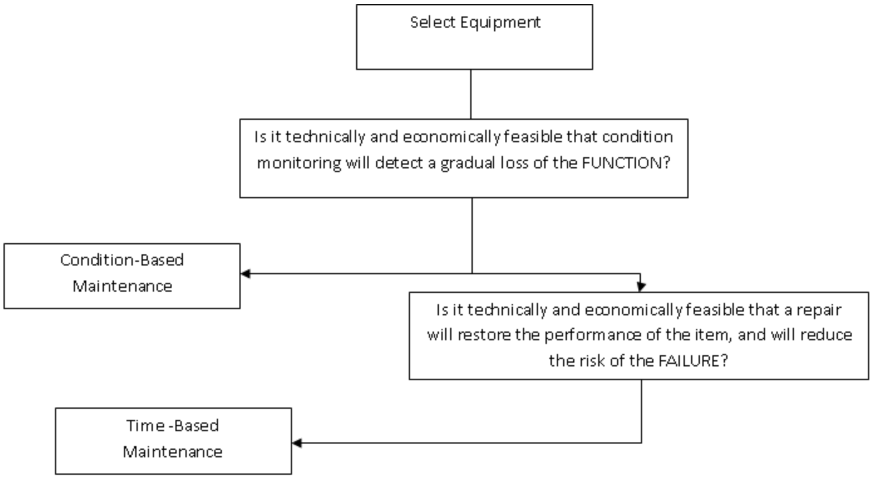

Figure 4 Partial RCM methodology logic (Jardine and Tsang, 1995)

Furthermore, it is given that a component within the maintenance kit is subjected to condition monitoring, it must be proven that this is also an economical feasible solution. This paragraph covers the topics and requirements which must be checked when considering CBM as maintenance strategy for a maintenance job. First the technical requirements are discussed after which an economical evaluation method is proposed.

### 4.2.1. System maintenance decomposition

The current composition, Small, Major and Total maintenance kits is not ideal when considering the implementation of condition monitoring such that a CBM policy can be used. Nevertheless, the current system decomposition and maintenance structure cannot be totally ignored due to technical consideration. Currently, a large maintenance kit contains C and D components. If the maintenance decision point is at a subassembly level and a C component which is in both overhaul packages is the performance indicator we must assume that the C part is also representative for the D parts. This can complicate things because the D parts have a much longer life time. To resolve this problem a new structure is proposed which is shown in Figure 5.

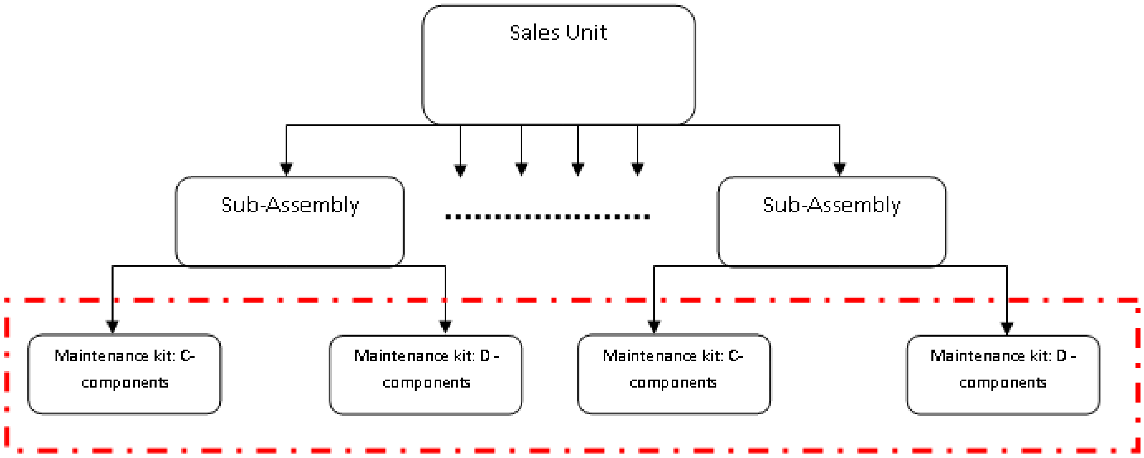

Figure 5 New system decomposition for maintenance purposes

Figure 5 shows that in the new decomposition the C & D parts are divided into new and separate C& D maintenance kits. The new decomposition allows the maintenance kits to contain components in a sub-assembly which from a mechanical perspective should be replaced at the same time as well as their failure times are approximately the same.

### 4.2.2 Technical requirements

#### *Functions*

To be able to assure that the physical assets continue to do what their users want them to do, it must be known what the owners demand of the asset. Hence, the first technical requirement is to define the functions of each asset in its operating context, together with the associated desired standards of performance. The implementation of a CBM program is mostly to assure what Moubray (1997) calls the primary functions of an asset. The primary functions of an asset summarize why the asset is installed in the first place (Moubray, 1997). Organizations acquire physical assets for one, possibly two, seldom more than three reasons. This category of functions covers issues such as speed, output, carrying or storage capacity, etc. (Moubray, 1997).

#### *Functional Failure*

Once the functions of the asset under consideration have been defined, the question arises how can maintenance help achieve these functions. It can be assumed that the only occurrence which is likely to stop any asset of performing to the standard required is some kind of failure. Therefore, maintenance achieves its objectives by adopting a suitable approach to the management of failure. Hence, the possible failures which prohibit the system in question to perform its desired function must be identified. These failures are defined as ***functional failures***. Moubray (1997) defined a functional failure as: "*the inability of any asset to fulfill a function to a standard of performance which is acceptable to the user".*

### *Failure modes*

In the previous paragraph the term functional failure has been introduced which defines when the system is in a failed state. Nevertheless, the functional failures do not provide information regarding the events which will cause the failed state. The next step in the search to find the right condition indicator (CI) is defining all the events which are reasonably likely to cause each failed state. These events are known as ***failure modes***. Resulting in the following definition: "*A failure mode is any event which causes a functional failure*" (Moubray, 1997). According to Moubray (1997) the point at which maintenance is managed is not at the level of the asset as a whole, and not even at the level of any component, but at the level of each failure mode. Thus to develop a CBM strategy for any asset, the failure modes must be identified. Furthermore, it must be noted that not all failure modes must be dealt with by a CBM strategy. It can be the case that some are not applicable or are not worth including in a CBM strategy.

Once each failure mode has been identified, it then becomes possible to consider what happens when it occurs. These revelations are also known as failure effects. Moubray (1997) defined a failure effect as: "*a description of what happens when a failure mode occurs".* A description of failure effects should include all the information needed to support the evaluation of the consequences of the failure. Once the failure modes have been linked to the malfunctioning of certain components or sub-assemblies, the different failure modes can be reviewed regarding their appropriateness for a CBM program. The appropriateness can be determined from the description of the failure effects. This is done by determining the failure mode is caused by a hard or a soft fault. This will be discussed in the next paragraph.

### *Type of failure*

Martin (1994) described CBM to be a technique which makes planned maintenance possible based upon measuring the condition of all machine elements during the normal operation of the machine. Furthermore, according to Martin (1994) these measurements should allow the prediction of the time to failure for all elements and thus allow maintenance to be planned before any elements fails.

Martin (1994) distinguishes between two different types of faults. The **soft** (or trend) fault which develops gradually with time, a characteristic which is common under mechanical elements where wear and tear takes place causing a gradual degradation of the operation of the element. The gradual degradation is depicted in Figure 6. The second faults type is that of a **hard** fault, a hard fault is a fault which takes place instantaneously; the element is either on or off. It are the soft faults which are suitable to subject to condition monitoring, the gradual degradation leads to a predictable situation.

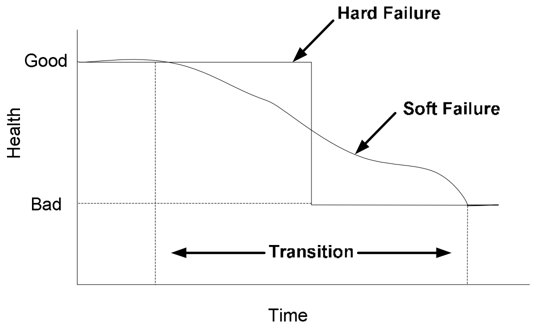

Figure 6 Degradation of different failure types

### *P-F Value and Interval*

Once a classification has been made for all failure modes which are the appropriate type of failures to be used for condition monitoring, the possibility of locating times of failures must be identified. As explained above the advantage of CBM is that it is possible to determine the “real” age of a component through condition monitoring. Moubray (1997) stated that; although many failure modes are not age-related, most of them give some sort of warning that they are in the process of occurring or are about to occur. Hence, here lies an additional advantage of CBM compared with a traditional age policy. By implementing a CBM policy it becomes possible to relate failure modes which are originally not age-related to an age or time related parameter. This means that if evidence can be found that a component is in its final stages of failure, it is possible to determine a more precise wear-out zone for each individual component based on its own condition.

According to Moubray (1997) the wear-out zone of an individual component can be projected by the so-called P-F curve. This curve which is depicted in Figure 7, it illustrates what happens in the final stages of failure. It shows how a failure starts, deteriorates to the point at which it can be detected (Point “P”) and then, if it is not detected and corrected, continues to deteriorate – usually at an accelerating rate – until it reaches the point of functional failure. The x-axis of the curve represents Time (T) or Operating Age, and the y-axis represents resistance to failure.  Starting at the top left part of the curve and moving right we encounter point P, known as Potential Failure.  This is the point in time that, when using some form of Predictive Technologies, one can first detect resistance to failure. The potential failure P, is an identifiable condition which indicates that a functional failure is either about to occur or in the process of occurring. In other words the potential failure is a condition value from which an accurate prediction becomes possible regarding the real time of the functional failure occurring, i.e. it is not an incidental chance in the condition. Hence, it is a threshold level which indicates the minimum value at which a user may make a replacement decision based on the condition of the component.

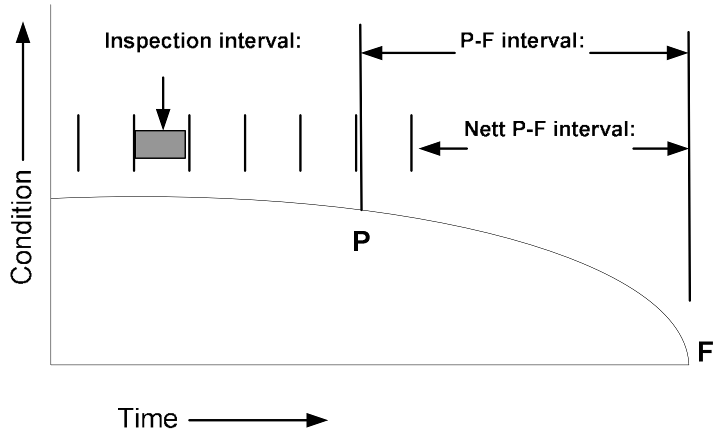

Figure 7 P - F value and interval

In addition to the potential failure itself, it is needed to consider the amount of time which elapse between the point at which the potential failure occurs and the point where it deteriorates into a functional failure (Moubray, 1997). Furthermore, Moubray (1997) defines the nett P-F interval, which is the minimum interval likely to elapse between the discovery of a potential failure and the occurrence of the functional failure. Both the P-F interval and Nett P-F interval are illustrated in Figure 7.

Concluding that when applying CBM to be able to organize the planning of maintenance several conditions must be met;

- It is possible to define a clear potential failure condition
- The P-F interval is reasonably consistent
- The net P-F interval is long enough to be of some use (in other words, long enough for action to be taken).

### *Threshold*

Previously two important values (Potential and Functional failure) have been introduced. These two failure values are condition values which must be predetermined to be able to implement CBM in such a way that it is able to predict when these two values will occur in time. The predefined values for the potential and functional failures are also named thresholds. These values determine the minimum and maximum time of replacement for each component.

According to Moubray (2002) to set the threshold, information must be gathered on what measurements can exist while equipment is running safely and what the measurements were just before or at the time of failure. Furthermore Moubray (2002) states that equipment manufacturers, and especially their experienced field representatives, are a good starting source of information. This concludes that there are two main sources of information by which a threshold can be determined.

- Expert opinion
- Historical data

When using expert opinion the two threshold levels are based on the experience of people who are familiar with the component under consideration. The use of historical data is a more accurate manner which provides more certainty although it is more difficult to collect. To make an accurate statistical estimation run to failure information is needed, such data sets are necessary to determine how much stress can be put on a device under actual operating conditions before it will fail. The estimation of the potential failure value is a bit more complex, here the data should be used to estimate the point from which the actual failure could have been statistically significantly determined.

### 4.2.2. Economical requirements

Besides the technical feasibility of CBM the decision scheme provided by Jardine and Tsang (1995) indicates the necessity to establish the economic feasibility of implementing a CBM tactic. In the maintenance literature this is a very under underrepresented subject. In the maintenance decision making literature only Khalil et al. (2005) significantly discusses a cost formula to help in the decision process. The formula and method provided by Khalil et al. (2005) is not sufficient to be able to indicate if it is economically feasible to implement CBM.

When considering a method to evaluate the economic feasibility there are two options. The first option is to simulate the behavior of the components in every maintenance kit and adjust the policy such that the maintenance kit is only replaced when and if the designated trigger part indicated that it must be replaced. The disadvantage of this method is that the fixed maintenance costs are not included. It only makes sense to include the fixed cost when providing a model which includes multiple maintenance kits such that the fixed cost can be shared. Hence, to evaluate the added value of implementing a condition based maintenance strategy, a planning and replacement strategy must be developed such that this can be evaluated. This is done in Chapter 5. Through applying the replacement decision model discussed in Chapter 4 the added value of implementing condition monitoring can be evaluated.

# 4. The condition based maintenance planning policy

Chapter 3 described the preconditions which are needed to be able to plan the preventive maintenance actions by the use of CBM. Besides the described preconditions the previous chapter stated the need of a planning policy. In this chapter a heuristic rolling horizon approach to the problem of joint replacement of multiple maintenance kits, where within each maintenance kit one component is subject to condition monitoring, is given. Paragraph 4.1 describes problem formulation regarding the planning of the preventive maintenance. After which Paragraph 4.2 describes the variables used, Paragraph 4.3 the assumptions on which the policy is founded and Paragraph 4.4 the rolling horizon concept used. Finally, Paragraph 4.5 describes the optimization model used in the policy.

## 4.1. Problem formulation

We consider a capital good system which contains a selection of critical parts which face a stochastic degradation process. These critical parts are the parts which will be leading for the maintenance scheduling of the whole system. The critical parts are the trigger parts which provide the information from which the time to replace a maintenance kit is derived. All critical (trigger) parts are subject to condition monitoring which provides failure specific information in the form of a Remaining Useful Life (RUL) distribution per maintenance kit. We assume that the parts are continuously monitored by various sensors to detect failures or performance malfunctions in real-time. The degradation process of each maintenance kit is divided into two parts: one which indicates the RUL of the trigger part before the wear-out process starts and a second part which indicates the RUL up to the functional failure of the trigger part. Within this context, each maintenance kit (represented by a trigger part) is considered as a maintenance job which is defined as a set of preventive maintenance activities. The set of maintenance activities exists of the replacement of each of the parts which are considered as one maintenance kit. Furthermore, each part is represented by the two RUL intervals and therefore the maintenance job can be executed at any given time t between these two time intervals. It is assumed that the execution of a planned maintenance job can only take place during a scheduled overhaul visit. These scheduled overhaul visits can only take place during the weekend due to the need of a complete plant shutdown to execute the maintenance and therefore the planned maintenance can only once a week. Therefore, the time (planning) horizon, TP, is discretized into a number of time periods of a weekly duration. The system is considered at these discrete time epochs, which will be called decision epochs. Due to the fact that each maintenance overhaul, therefore maintenance job, can only take place in the weekend, it is assumed that the decision epochs are equidistant. Additionally, there is also a lead time regarding the execution of the maintenance jobs. This means that it takes a certain time after the decision to replace has been made until it is actually executed.

As mentioned the lifetime of a maintenance kit is divided into two parts; the first part is the time until the point where it can be found out that a maintenance kit is failing; this is the potential failure point. Secondly, there is then the time where the maintenance kit fails, this is the functional failure of a sub-assembly. For both the RUL is the time interval between the actual point in time between obtaining the last data point and the point in time where a potential of functional failure occurs. This failure time differs for a particular unit. The RUL is a random variable following a probability distribution. The RUL can be modeled using a probability density function, which is denoted by the time to failure or by using the cumulative distribution function that describes the probability that a unit fails at or before a specific moment in time. Hence, the probabilities provided by the RUL are considered as one of the inputs for the multi-maintenance kit replacement decision making. Each part is assigned a predetermined probability of failure at each decision epoch t. The probability of failure at each decision epoch t denotes the probability that a sub-assembly failed during the period after decision epoch t – 1 and up to decision epoch t.

Furthermore, it is assumed that there are fixed and variable costs that can be assigned to a preventive maintenance overhaul. It is assumed that if at a decision epoch t a sub-assembly is still working, it can be replaced preventively against variable preventive maintenance costs. These variable preventive maintenance costs depend on the sub-assembly. The fixed costs are costs that are assigned to every maintenance visit (costs of an overhaul), independent of the amount of maintenance kits that are replaced. Hence, it is assumed that fixed costs occur once a decision is made to replace at least one maintenance kit at a decision epoch t. In the case that multiple maintenance kits are replaced at the same decision epoch t, then still only one fixed cost is assigned to the decision epoch t. Fixed costs may consist of maintenance-related costs (e.g. salaries, spare parts, tools, materials) as well as production-related costs (e.g. production loss, productivity loss, delay penalties). This concludes to the following situation; at every decision epoch t that a preventive maintenance is planned for at least one maintenance kit a fixed costs will be assigned to that decision epoch t. Hence, one objective of the scheduling model is the minimization of the fixed overhauls costs taking into account the variable costs. The second kind of costs is the variable replacement costs. The variable replacement costs are costs which can be assigned to a maintenance kit individually. The costs which can be assigned to a single maintenance kit are the cost of failure and the cost of premature replacement. These two costs are contradicting each other and therefore the optimal balance should be found based on the costs. The cost of premature replacement can be seen as a linear decreasing cost. This linear cost function is dependent on the time period used in the model. The cost of failure is not a linear cost function. The failure costs are simply computed by multiplying the probability of failure, based on the RUL, at a given decision epoch t with the costs of a failure occurring.

## 4.2. Variables used in condition based maintenance planning policy

### Sets

| | |
|---|---|
| **S** | Set of maintenance kits, which uses index s, such that $s \in S$ |
| **T** | Set of discrete time periods (weeks), which uses index t, where TP = {1,2,……….,T} |

### Parameter declaration

| | |
|---|---|
| **CDT** | Downtime cost per time unit for maintenance kit $s \in S$. |
| **$CEU_s$** | The cost of an emergency maintenance kit, needed when an unexpected failure occurs, for maintenance kit $s \in S$. |
| **CMT** | These are the costs of a maintenance technician who is needed to execute the preventive replacement. These costs are indicated per hour. The costs are exists of the hourly salary of the technicians needed. |
| **CPE** | The salary rate of a production employee at the client per time unit. |
| **CSE** | Cost of Senior Service Engineer needed to execute the preventive maintenance. |
| **$CT_s$** | These are the normal transportation costs of maintenance kit $s \in S$. Normal transportation costs occur when a maintenance kit $s \in S$ is transported to a client at a preplanned date. |
| **$CU_s$** | The sales price of a maintenance kit $s \in S$; this is the cost that is assigned to a unit within the model. |
| **DEC** | Reimbursement of the daily expenses of the Senior Service Engineer during the planned maintenance overhaul. |
| **$ECC_s$** | Expected replacement costs per cycle maintenance kits $\in S$. This expected costs is based on the initially indicated individual replacement time $t^*$ for maintenance kit $s \in S$. |
| **$EERT_s$** | Expected emergency repair time after an unexpected failure from maintenance kit $s \in S$ has occurred. |

| | |
|---|---|
| $\mathbf{ERT_s}$ | Expected repair time for a normal planned replacement during a planned overhaul for maintenance kit s ∈ S. |
| **ETP** | This is the emergency transportation penalty. This is a penalty that is assigned to the transportation of a single maintenance kit s ∈ S which must be sent to the customer in the case of an unexpected failure. This penalty is a fraction of the original transportation rate. |
| **FCM** | Fixed cost of executing a maintenance visit (executing a maintenance overhaul). |
| **L** | This is the lead time that it takes to execute the replacement after the decision to replace has been made. |
| **NPE** | The number of production employees that are directly involved in the production line. |
| $\mathbf{t_s^*}$ | Expected optimal replacement times for maintenance kits ∈ S |
| **TVC** | The travel costs that occur when a Senior Service Engineer must visit the customer for a preventive maintenance execution |
| $\mathbf{q_t^s}$ | The probability that maintenance kit s ∈ S will fail between decision epoch t -1 and t. Hence, regardless of the state of the component at decision epoch t -1 that the component will fail when going form decision epoch t – 1 to decision epoch t. |
| $\mathrm{FF^s}$ | Is the time at which a functional failure will occur. A functional failure is the inability of the maintenance kits trigger part to fulfill a function to a standard of performance which is acceptable to the user. |

### Decision variables

$$\mathrm{x_t^s}\begin{cases}1 & \text{Maintenance kit s is replaced at time period t}\\ 0 & \quad\text{else otherwise}\end{cases}$$

$$\mathrm{y_t}\begin{cases}1 & \text{Fixed replacement cost have been assigned at time period t}\\ 0 & \quad\text{else otherwise}\end{cases}$$

## 4.3. Assumptions

- Each period only two events can occur concerning the component condition. Either the components fails in period t with a probability of $q_t^s$ or the component does not fail with a probability 1- $q_t^s$. This is a commonly used assumption in maintenance management models. Although in reality a component can be slightly damaged in some cases and does not have to be replaced but only repaired. Due to the unpredictability of such a situation the above assumption is made.

- The probability of the event occurring in period t is independent of what has occurred up to period t -1. This assumption is made to indicate that once time t has arrived the state of the system is known at the start of time t and therefore we only take into consideration the events that can occur in period t given that the state of the system is known at the start of period t.
- We assume that if a maintenance kits trigger part fails that an emergency replacement occurs in this emergency repair the components in the maintenance kit is as good as new. Hence, an unexpected failure is not a possibility to execute the planned overhaul maintenance.
- There is only one kind of maintenance technician; this technician is able to execute all preventive maintenance activities. This is a accurate representation of the reality. The components which are taken under consideration are by far mostly mechanical components and therefore replaced by a mechanical technician.
- We assume technical independency. This means that the degradation of one critical component and therefore the maintenance kit does not interact with any other components. This assumption is made because the failure indicators extracted through condition monitoring are gained on a component level. Therefore there is only one condition indicator.
- We assume ample time during the overhaul opportunities to replace any amount of maintenance kits needed. This assumption is not conforming to reality. If implementing a preventive maintenance plan we are confronted with limited time. These are the hours provided in the weekends when maintenance is executed. Only the issue of time constrained overhaul opportunities only is of significance when implementing in a large scale. Giving that this project focuses only on one type of machinery for the time being this assumption is made.
- It is assumed that the expected functional failure times ‘FF’ is projected on a weekly interval. This means that a functional failure ‘FF’ can only occur at a decision epoch t.
- We assume that that for each maintenance kits trigger part the P-F interval is larger than one week. This is a necessity; if this is not the case a maintenance kit cannot be included in the model due to the fact that the decisions are made on a weekly basis. If it is not possible to detect a failure at least a week before occurring there is no sense in planning it trough condition monitoring.

## 4.4. Planning Horizon

The multi-component scheduling for systems subject to condition monitoring has many resemblances with what is called Model Predictive Control (MPC). This is an advanced method of process control that is used mostly in the process industries. MPC is based on iterative, finite horizon optimization of a plant model. At time *t* the current plant state is sampled and a cost minimizing control strategy is computed (via a numerical minimization algorithm) for a relatively short time horizon in the future: $[t,\ t + T]$. Specifically, an online or on-the-fly calculation is used to explore state trajectories that emanate from the current state and find a cost-minimizing control strategy until time$t + T$. Only the first step of the control strategy is implemented, then the plant state is sampled again and the calculations are repeated starting from the now current state, yielding a new control and new predicted state path. The prediction horizon keeps being shifted forward and for this reason MPC is also called “receding horizon control”. Although this approach is not optimal, in practice it has given very good results.

To solve the scheduling problem of a multiple components system subject to condition monitoring we suggest an approach which is similar as the MPC method. The model that we propose is part of a rolling scheduling technique which makes use of a finite horizon optimization. Because it is a finite horizon optimization the determination of the planning horizon T is of major importance. To determine this horizon the following criteria is determined. At each decision epoch t the RUL parameter of each maintenance kit $s \in S$ is a given. As mentioned in the previous chapter with the help of the RUL one parameter can be determined; a time-based value to indicate the expected time up to the ‘FF’ value.

The value ‘FF’ provides the maximum replacement time based on the technical consideration of the parts. Given the dynamic character of the continuous predictions, the sequence of the maintenance kits which must be replaced, can change. To take all possible options under consideration in the optimization the finite horizon of the optimization each scheduling opportunity is determined by the maintenance kit with the most postponed functional failure time. Hence, to determine the end horizon T for the finite horizon optimization we suggest that the horizon T is determined by the following statement; $max\{F^S\}\ \ s \,\forall\, S$. Figure 8 shows a graphical example of how the theory works.

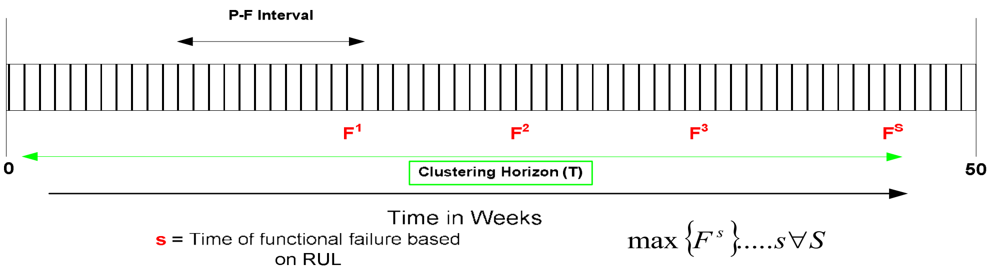

Figure 8 Graphical representation of the planning horizon

## 4.5. The multi- kit replacement model

The proposed maintenance replacement scheduling model is a rolling scheduling model which only contains at most one of each component s ∈ S within the planning horizon. The time horizon, TP, is discretized into a number of time periods, t, of a weekly duration. The replacement planning optimization model has as goal to minimize the costs of four aspects of the maintenance problem. These four aspects are presented below and will be discussed separately afterwards.

1. The cost of executing a corrective maintenance replacement due to a failure of a maintenance kits trigger part;
2. The cost of executing a preventive maintenance for a maintenance kits trigger part;
3. The cost of premature replacement when executing clusters within the preventive maintenance overhauls;
4. The fixed cost which occur when visiting a customer to execute a maintenance overhaul.

### 4.5.1. Costs of corrective replacement

The expected costs of executing a corrective maintenance are one of the costs aspects that must be minimized. Due to the uncertainty in the degradation process the possibility of a failure before expected can always occur. To take this uncertainty into account the costs which occur when an unexpected failure takes place must be taken into account in the model. The costs which are assigned to an unexpected failure are; costs of downtime; costs of maintenance technician needed to resolve the failure and the costs of an emergency unit.

**Expected emergency repair time (EERT)**

When an unexpected failure occurs this failure must be resolved by a maintenance kit replacement such that the system and therefore the production line are back online. It is assumed that the work that arises when an unexpected failure occurs is executed by a maintenance technician who is onsite. This maintenance technician executes an emergency repair. For the emergency repair it is assumed that the technician executes an emergency solution such that the system can work accordingly and that when the emergency maintenance kit arrives this is replaced during non-production hours. For every maintenance kit$s \in S$ an expected emergency repair time ($\mathrm{EERT}_s$) is defined. This $\mathrm{EERT}_s$ is a fixed expected time that it takes the technician to execute the emergency solution if maintenance kit $s \in S$ fails. The time that it takes the technician to replace the new components within a maintenance kit once arrived, which is done outside of production hours, is included in the cost of an emergency unit. It is assumed that the emergency solution brings back the systems production level to the same level of a new sub-assembly and that it does this until the new sub-assembly arrives and is installed.

**Costs of downtime (CDT)**

The costs of downtime arise from an unplanned production stop due to a failure of a maintenance kits trigger part. We assume that once a failure of maintenance kits trigger part occurs an unplanned line stop arises. Hence, the whole production line becomes down for the amount of time that it takes to repair the maintenance kit. The costs of the downtime are estimated by providing an assessment of the number of direct production personal that are directly involved in a line stop. The number of personal involved when a line stop occurs is multiplied with the local hourly rate of the personal. This is important because the hourly rate can differ drastically depending on the geographical location of the client in question. Hence;

$$CDT = NPE \cdot CPE$$

**Cost of maintenance technician (CMT)**

The cost of the maintenance technician is an hourly rate. This is a fixed cost which is assigned as variable costs because it is depended on the amount of time a technician must spend on a certain maintenance kit. This cost is multiplied with the $\mathrm{EERT}_s$, which is maintenance kit depended.

**Cost of Emergency Unit (CEU)**

The cost of an emergency unit arises when a maintenance kits trigger part fails unexpectedly and a maintenance kit must be sent to the customer per emergency transshipment. These costs entail several aspects; the cost of the subassembly $s \in S$ itself; emergency transportation costs; costs of replacing the new sub-assembly itself outside of production hours. Hence, the costs of an emergency unit are;

$$CEU_s = CU_s + CT_s \times (1 + ETP) + ERT_s \times CMT$$

The cost of the maintenance kit$s \in S$ itself is the same sales price which is factored to the customer for the consumption of the maintenance kit. Furthermore, the emergency transportation cost is computed by multiplying the standard transportation cost for a maintenance kit$s \in S$ times the extra penalty fraction. The penalty fraction is added because due to the emergency the maintenance kit cannot be transported in groups but must be transported in its own making use of a special express. Finally, as previously mentioned the cost of installing the new maintenance kit also contributes to the cost of an emergency unit. This cost is the multiplication of the expected repair time of a maintenance kit $s \in S$ times the cost of the maintenance technician. Despite the fact that this is done outside production hours it is assumed that the cost of the technician is still the normal hourly rate.

### 4.5.2. Costs of preventive replacement

The expected cost of executing a preventive replacement is the second cost aspect that must be minimized. As previously explained due to uncertainty there is always a probability that an unexpected failure occurs between two decision epochs. Nevertheless for every decision epoch t there is also the probability that a preventive maintenance can be executed. The preventive maintenance activities can only take place during the weekends and therefore at the decision epoch t. The costs of a preventive maintenance consist of two elements; costs of planned replacement and the cost of the maintenance kit.

**Cost of planned replacement**

The costs of a planned replacement are the cost that arise when replacing a maintenance kit$s \in S$at a given decision epoch t before a failure has occurred. These costs are maintenance kit depended. This means that every maintenance kit$s \in S$ is assigned a planned replacement costs. These costs consist of the expected replacement time ($ERT_s$) and the cost of a maintenance technician (CMT). These two elements are multiplied and provide the costs of the planned replacement.

**Cost of maintenance kit ($CU_s$)**

The cost of the maintenance kit is simply the sales price which is assigned to the maintenance kit in question.

### 4.5.3. The costs of premature replacement

Thirdly, there is the cost of premature replacement. The costs of premature replacement are costs that occur due to not fully fulfilling the total lifetime of the component. The costs of premature replacement are represented by the expected number of cycles that will occur within the time horizon T if a maintenance kit is replaced at time t. As explained the maintenance kits trigger part within the system can have different lifetimes. The construction of the horizon of the optimization model leads to a situation that a given maintenance kits trigger part can have multiply cycles within the planning horizon. The possibility of having multiple cycles within the horizon makes it necessary to make an estimation of the expected cycle costs after the current component is replaced or fails. This can only be done by estimation. This estimation is based on the optimal replacement time of each maintenance kits trigger part individually depending on the age of the maintenance kits trigger part. The estimate the expected cost of a component for the rest of the horizon after being replaced or have failed depends on the two factors; first, the expected number of cycles and secondly, the expected replacement cost per cycle.

**Expected number of cycles**

Given that a maintenance kits trigger part fails or is replaced at any given time t, the expected number of cycles can be computed as following;

$$expected\ number\ of\ remaining\ cycles = \left(\frac{T-t}{t^*}\right)$$

The statement above shows that the expected number of remaining cycles is dependent on three things. The total horizon T, the current time t and finally the expected optimal replacement time (age). The first two are rather straightforward, the third parameters requires some further explanation. The determination of the expected optimal replacement time for the sub-assemblies is done by balancing the cost of the previously described preventive replacements against their benefits, this is done by determining the optimal preventive replacement age for the item to minimize the total expected costs of replacements per time unit. The replacement policy that is used to determine the optimal expected replacement age for the subsequent components corresponds with that of the general model that will be described later. The replacement policy is to perform a preventive replacement when the item has reached a specific age $t^*$, plus failure replacements when necessary. There is no real-time degradation data known for the subsequent maintenance kits trigger part as they are not implemented in the system yet. This leads to the need to estimate the expected failure times with a probability density function $f(t)$, which is based on the known averages. Finally, the objective here is to determine the optimal replacement age of the item to minimize the total expected replacement costs per unit time. As in the general multiple component model described later there are two possible cycles of operation: one cycle being determined by the item reaching its planned replacement age $t^*$ and the other being determined by the equipment ceasing to operate due to a failure occurring before the planned replacement time. This leads to the following function which describes the expected replacement cost per time unit (ERCTU).

$$\text{ERCTU} = \frac{total\ expected\ replacement\ costs\ per\ cycle}{expected\ cycle\ length}$$

When describing the above cost function mathematically with the corresponding costs and parameters this leads to the following formulation.

$$\text{ERCTU} = \frac{\big((CDT + CMT) \cdot EERT_s + CEU_s + (ERT_s \cdot CMT)\big) \times F(t) + (ERT_s \cdot CMT + CU_s) \times (1 - F(t))}{\int_0^t t[1 - F(t)]\, dt}$$

When optimizing the above equation for every maintenance kit individually, such that the cost are minimized, the optimal replacement age $t^*$ can be determined for every maintenance kit.

**Expected replacement costs per cycle (ECC)**

The ECC is a fixed costs which is the expected costs that are assigned to a cycle given that a maintenance kit is preventively replaced at a certain time t. Just as with the multiple components optimization model the expected replacement costs per cycle contain expected cost of a preventive maintenance and the expected cost of a failure occurring. According to Jardine and Tsang (2006) the ECC is the cost of a preventive cycle times the probability of a preventive cycle plus the cost of a failure cycle times the probability of a failure cycle. This can be stated as following:

$$ECC = (ERT_s \cdot CMT + CU_s) \times \big(1 - F(t)\big) + \big((CDT + CMT) \cdot EERT_s + CEU_s\big) \times F(t)$$

When knowing the individual expected optimal replacement age t*, which is determined as previously described, for each maintenance kit the expected cost of a cycle can be computed.

### 4.5.4. Fixed costs per planned overhaul visit.

For the fixed setup costs, which occur for every planned overhaul, we assume that one Senior Service Engineer is provided by MSPP. This Senior Service Engineer is needed by the client to supervise the execution of the maintenance repairs. For every overhaul visit the Senior Service Engineer arrives at the client at Friday and returns back on Tuesday. Hence, for every visit at the client for an overhaul the costs of the Senior Service Engineer are assigned to the maintenance replacement. Furthermore there are accommodation costs, daily expense cost and so-called kilometer costs. The kilometer costs are the costs that occur due to the need for the Senior Service Engineer to travel back and forth to the client. Hence the fixed cost of maintenance is constructed as following;

$$FCM = CSE + AC + DEC + TVC$$

Fixed costs are assumed to be the same for all maintenance overhauls, it does not matter which maintenance kits are included.

### 4.5.5. The linear binary constrained optimization model

To optimize the above described costs functions an objective function has been developed which minimizes the expected costs over the planning horizon T for all maintenance kits$s \in S$. The objective function is a combination of the described costs, the output of the prognostics models in the form of probabilities and minimal and maximal replacement times, binary decision variables and finally a set of constraints regarding the binary decision variables. To determine at which decision epoch t, a maintenance kit $s \in S$ should be replaced a binary decision variable $x_t^s$ is introduced. Furthermore, a second binary variable is denoted as $y_t$ determines when a fixed overhaul costs is assigned to decision epoch t. The three elements have led to a non linear optimization problem with binary variables. The objective aims to minimize the expected cost of corrective maintenance, expected costs of preventive maintenance, including the variable and the fixed overhaul costs and the cost of premature replacement. The according mathematical formulation is provided as following.

$$\begin{aligned}
&\sum_{s\in S}\sum_{t=1}^{T}\Bigg[\Bigg[\sum_{j=1}^{t}\Bigg[\left(1-\sum_{i=0}^{j-1}(q_i^s)\right)\cdot q_j^s\cdot\left[\left((CDT+CMT)\cdot EERT_s+CEU_s\right)+\left(\frac{T-j}{t_s^*}\right)\cdot ECC_s\right]\Bigg]\Bigg] \\
&\qquad +\Bigg[\left(1-\sum_{z=0}^{t}q_z^s\right)\cdot\left[(ERT_s\cdot CMT+CU_s)+\left(\frac{T-t}{t_s^*}\right)\cdot ECC_s\right]\Bigg]\Bigg]\cdot x_t^s \\
&\qquad +\sum_{t=1}^{T}FCM\cdot y_t
\end{aligned}$$

Subject to:

$$\sum_{t=F^s+1}^{T} x_t^s = 0 \qquad \forall s\in S$$

$$q_0^s = 0 \qquad \forall s \in S$$

$$x_t^s, y_t, \in \{0,1\}, \qquad \forall s\in S, \qquad t\in\{1,\ldots,T\}$$

As can be seen the objective function consists of two parts. The first part minimizes the cost of corrective maintenance, cost of preventive maintenance and premature replacement for all maintenance kits $s \in S$ for all decision epochs $t \in T$. For every maintenance kit at each decision epoch t the expected cost of a corrective replacement are computed. The expected cost of a corrective maintenance action is a summation of the probabilities of all possible failure scenarios up to decision epoch t multiplied with the corresponding cost of a failure and therefore an emergency replacement and the cost of the expected remaining cycles. Secondly, the cost of a preventive replacement are minimized by multiplying the cost of a preventive replacement plus the cost of the expected remaining cycles when replaced at decision epoch t times one minus the cumulative probability that the component will still be up in decision epoch t. The costs of premature replacement are taken into account by including the expected number of cycles still to come within the planning horizon T when a component fails at time t or is preventively replaced at time t. These costs of the expected number of cycles are dependent on the time t within the optimization model and the probability that a failure or preventive maintenance can occur at time t.

An example for how the different probabilities are computed given for example the expected cost of replacing at epoch t is graphically shown in Figure 9. For the second part of the objective function, the fixed overhaul costs are multiplied times the binary decision variable $y_t$. This binary variable denotes that when a planned overhaul is executed a fixed cost is also assigned to the decision epoch in question. The other binary decision variable $x_t^s$ denotes the planned replacement time for each maintenance kit$s \in S$.

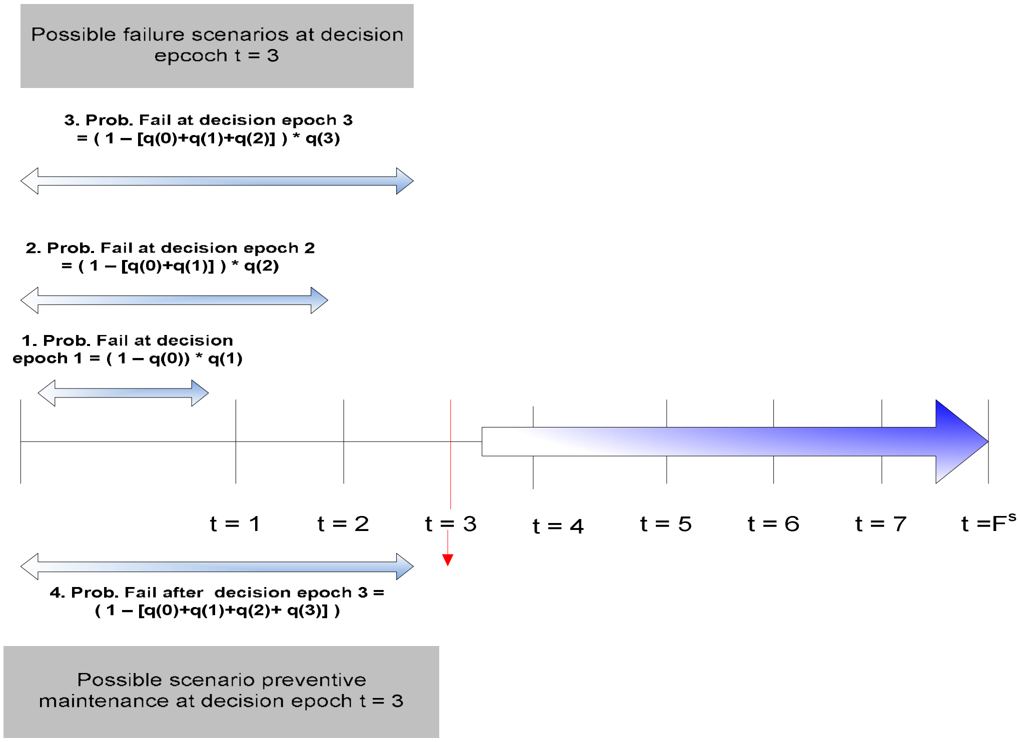

Figure 9 Computation expected cost at any given time unit t

Furthermore, several constraints are introduced to incorporate the operational restrictions into the optimization. Constraints (1) define the interval in which a maintenance kit may be replaced. Hence, they define the boundaries for the possible locations of the replacements; these are between the current time and the time of a functional failure occurring. Constraint (3) ensures that at time zero the cumulative failure probability is always zero. Constraints (4) ensure that if time period $t \in T$ will be used for at least one replacement that the according fixed costs regarding a maintenance visit are assigned to that time $t \in T$. Finally, Constraints (5) ensure that the decision variables are binary.

# 5. Application Planning model at MSPP

In chapter 3 and 4, the decision process to decide if a CBM policy is technically and economically feasible, is discussed. This chapter presents the application of the decision process at MSPP. This chapter will only contain more details regarding the economical maintenance optimization model. Therefore, it is assumed that for all components or sub-assemblies included in this chapter CBM is technically feasible. To demonstrate the working of the decision process one particular maintenance kit has been selected. Paragraph 5.1 will describe the business case chosen to provide more insights regarding the designed CBM policy. Subsequently, paragraph 5.2 will discuss how the degradation processes of the critical parts are estimated. To provide more significant insights regarding the CBM policy, it is compared to two different additional policies. These are discussed in Paragraph 5.3. Furthermore, paragraph 5.4 states the data which is used during the case. Finally, paragraph 5.5 will display the results regarding the different policies to provide MSPP with some more insights.

## 6.1 Case setting at Marel Stork Poultry Processing

Chapter 2 discusses the wide assortment of machinery provided by MSPP. A small part of this assortment is chosen to apply a small business case. Furthermore, it was described that MSPP has customers located world-wide. The geographical location of a customer is of major significance because these influence the build-up of the relevant cost. Additionally, each type of machinery has its own set of characteristics such as number of critical components, number of sub-assemblies etc. Therefore the business case is based on a customer's location and the chosen machine.

### 6.1.1. Location Business case

The chosen location of the type of customer that will be observed in the business case is Western-Europe. More specifically, the business case will focus on the modern type of customers within Western Europe. These customers characterize themselves by having highly automated processes. Furthermore, these types of customers in Western Europe have production days of 16 hours which has as consequence that downtime costs become extremely high. Naturally, the other costs are also affected. The shared fixed costs that are assigned each time that a maintenance mechanic of MSPP has to visit the customer are relatively low compared to visits to locations that are located farther away. Concluding that for a customer profile like this the corrective maintenance costs are extremely high compared to the preventive maintenance costs as well as the to the shared fixed costs.

### 6.1.2. Selected machinery and associated parameters

In the introductory chapter 2, it is described that a customer's production facility exist of a production line which is decomposed into process lines, which again is decomposed into several sales units which is constructed through the mechanical composition of several sub-assemblies.

Figure 10 graphically shows the decomposition of the production line up to the chosen sales unit for this business case. The sales unit that is applied during the business case is the so-called Transfer System. The transfer system is located in the plucking process. The sales unit may, in turn be decomposed into several sub-assemblies.

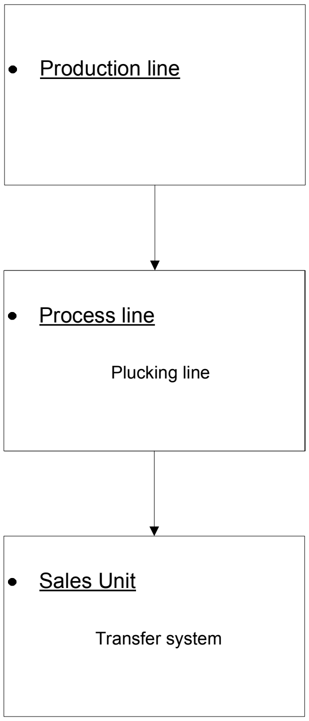

Figure 10 Decomposition production line for business case

In its full form the Transfer System can be decomposed into 13 sub-assemblies. Due to the extensiveness for such a research 3 sub-assemblies have been determined to take part in the business case. These are;

- The sub-assembly for the chain transport of the system, also known as Chain.
- The sub-assembly for the gear unit of the system, also known as Gear Unit.
- The sub-assembly for the transport function of the system, also known as Transport.

As Figure 11 shows each sub-assembly can be further decomposed into maintenance kits, which also has been described in Paragraph 4.2.1 and by Figure 5. The maintenance kits are a selection of parts of the sub-assembly which due to life time and mechanical constraints must be replaced simultaneously. Each maintenance kit has one critical component which determines the expected life time of these components.

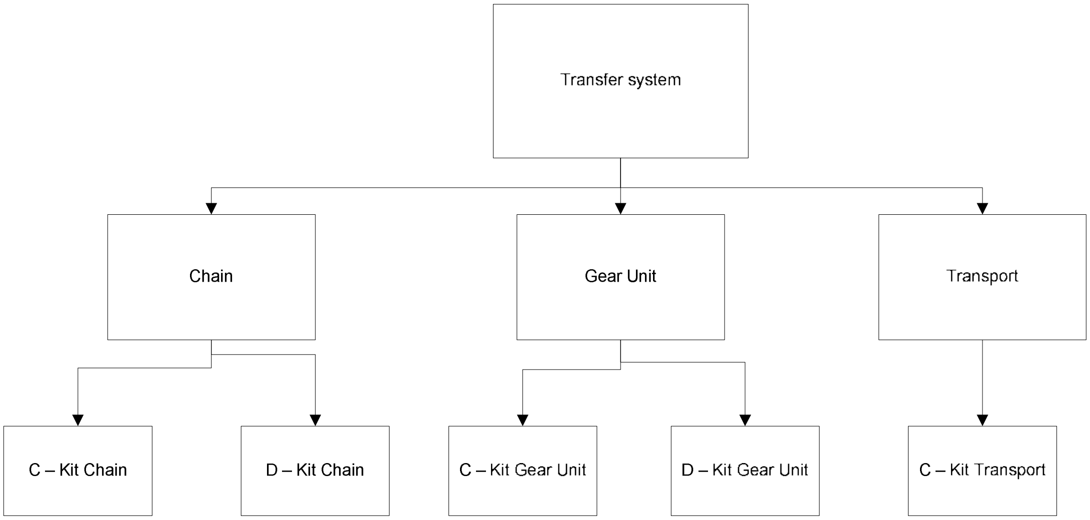

Figure 11 Decomposition transfer system

## 6.2. Remaining useful life generation

The business case for the Transfer system is designed to investigate what the possible effect of using the designed CBM policy will be given a certain average degradation process is assumed for the critical components of each maintenance kit. The current situation at MSPP is such that only expert opinions are known regarding this component degradation and no exact statistical information exists.

Based on these expert opinions an expected degradation process is designed for each critical component of each maintenance kit included in the business case. The design of the expected degradation process into a statistical format is done by using a distribution drawer provided by the so-called Microsoft add-in @Risk. The expected degradation process for each critical component is drawn as a cumulative distribution function (CDF). The CDF describes the probability that the critical component of the associated maintenance kit fails before a specific moment in time, denoted by $F(t)$. Equation 1 shows the mathematical formulation of such a CDF.

$$F(t) = \ Prob\ (\ Kit\ failure\ at\ or\ before\ T) = \ Prob(t \leq T) = \int_0^T f(t)\, dt \qquad (1)$$

The initial estimation of the degradation process is based on two main characteristics;

- The form of the expected degradation and;
- The maximum expected lifetime.

Figure 12 shows the fitting of an initial estimation of the degradation process of a component. Figure 12 shows two expected life time distributions. The blue line is the initial estimated life time distribution based on the expert opinion of the mechanics. Here it was important to determine what according to them the maximum life time of the critical component is and what is a reasonable estimation of the probability of failure is at a given time to determine the shape of the CDF.

It should be noted that the engineers provided a final time at which they expected the component to failure for sure. The reasoning behind this idea is that the current maintenance policy of MSPP is based on this reasoning. Nevertheless, technically and theoretically this would not be correct and therefore when fitting a distribution the life time is assumed to be up to infinity. This causes a slight difference between the life time drawing provided by the engineers and that of the fitted distribution.

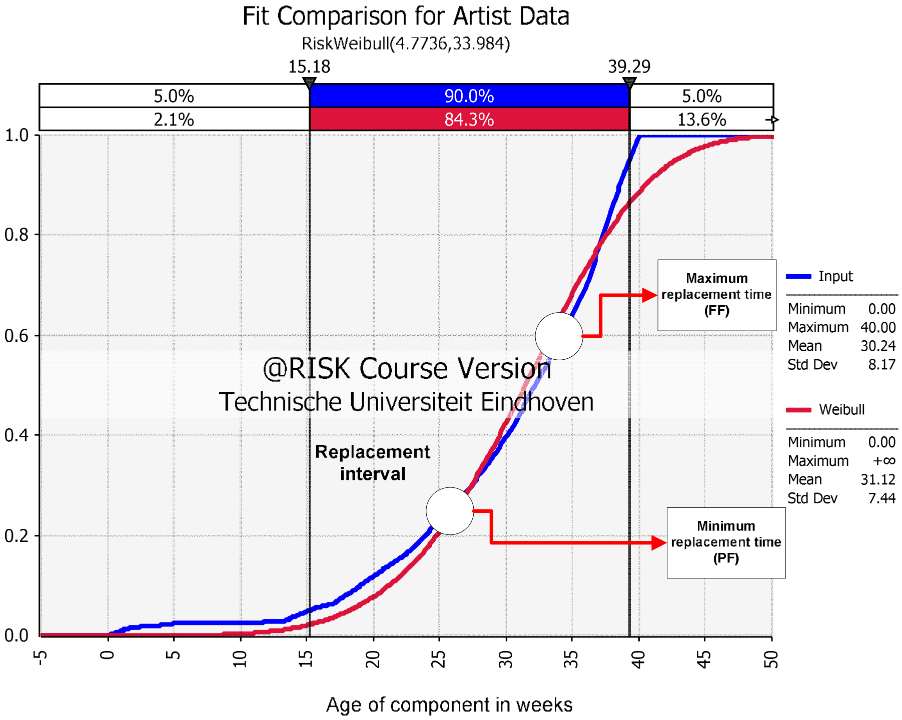

Figure 12 Estimation of degradation process critical component

## 6.3 Maintenance policies

Previously mentioned is that the objective of the business case is to discover the added value of the designed CBM policy. The added value only becomes clear when compared with different policies. Therefore, three policies have been determined. These policies denote;

- CBM Policy: A CBM policy which includes the method and model described in chapter 5;
- Marel Stork policy: The current policy used by MSPP regarding the maintenance kits included in the business case;
- 95 % policy: This third policy replaces the maintenance kits at every time t given a fixed replacement interval. This fixed interval is based on an interval time such that on average 95 % of the failures on the long run will be avoided.

The latter two policies provide two relevant insights. First, the policy used by MSPP does not anticipate a change in the expected long run average life time. Therefore, the policy used by MSPP can be classified as a policy which is set given that the real average lifetime is unknown. This in comparison with the last policy which has historical failure data and based on that data determines a fixed replacement interval for each maintenance kit. Finally, the first two policies make use of a clustering technique whereas the last policy does not. This to provide insight regarding the efficiency of clustering compared with a strict reliability rule.

### 6.3.1. The CBM policy

The policy starts with an initialization in which the data regarding the three different kinds of costs structures are implemented, these being; preventive maintenance costs; corrective maintenance costs and shared fixed costs. An associated phenomenon of CBM is that it is naturally not possible to immediately have enough data such that a prediction methodology can be used. Therefore a decision must be made if there enough condition related data has been collected to be able to model a RUL distribution. This decision has two options;

(i) Use the initial expected life time to model the RUL distribution, when answer is negative;
(ii) Use the gathered information regarding the condition to model a new RUL.

In the current project there is no condition data at hand as there are no associated actual failure times regarding the components. Therefore the updating of new information is done with random generated failure data and an interpolation technique. Formula 1 provides the formula how the expected failure time at time t is determined.

$$\begin{aligned} &Failure\ information\ time\ t \\ &\quad = expected\ failure\ time + (t-5) \\ &\quad \times \left(\frac{generated\ failure\ time - expected\ failure\ time}{generated\ failure\ time}\right) \end{aligned} \tag{1}$$

Once the information regarding the expected failure time is implemented either way the new RUL distribution is computed. The RUL is the time interval between the actual point in time between obtaining the last data point and the time where failure occurs. The RUL is uncertain and is modeled by a random variable following a probability distribution. The RUL is modeled using the cdf that describes the probability that a unit fails before a specific moment in time, denoted by $F(t)$.

$$F(t) = Prob\ (component\ failure\ at\ or\ before\ T) = Prob(RUL \leq T) = \int_0^T f(t)\, dt \tag{2}$$

Here the model still assumes that at each time t the RUL distribution will follow a Weibull distribution with a given shape. Given that the expected failure time and the shape parameter (α) are known, leaving only the scale parameter (β) of the Weibull distribution unknown. The scale parameter is therefore computed through the following equation;

$$\beta = \frac{expected\ failure\ time}{\Gamma\left(1 + \frac{1}{\alpha}\right)} \tag{3}$$

Once the RUL distribution is known, it provides two major input variables for the model;

- The maximum time of failure ($F_s$), which is the expected time of failure;
- The expected failure probabilities for each time period t, these provide the model with the probability that a critical component $s \in S$ fails ($q_t$) in any given time period t.

$$q_t = \int_0^t f(t)\, dt - \int_0^{t-1} f(t)\, dt \tag{4}$$

Once all these input variables are known, the replacement model can run. In the case the model determines that a component must be replaced with at a time t which is within the decision lead-time a component must be replaced. Otherwise the decision to replace is at least delayed up to the next decision moment in period t + 1.

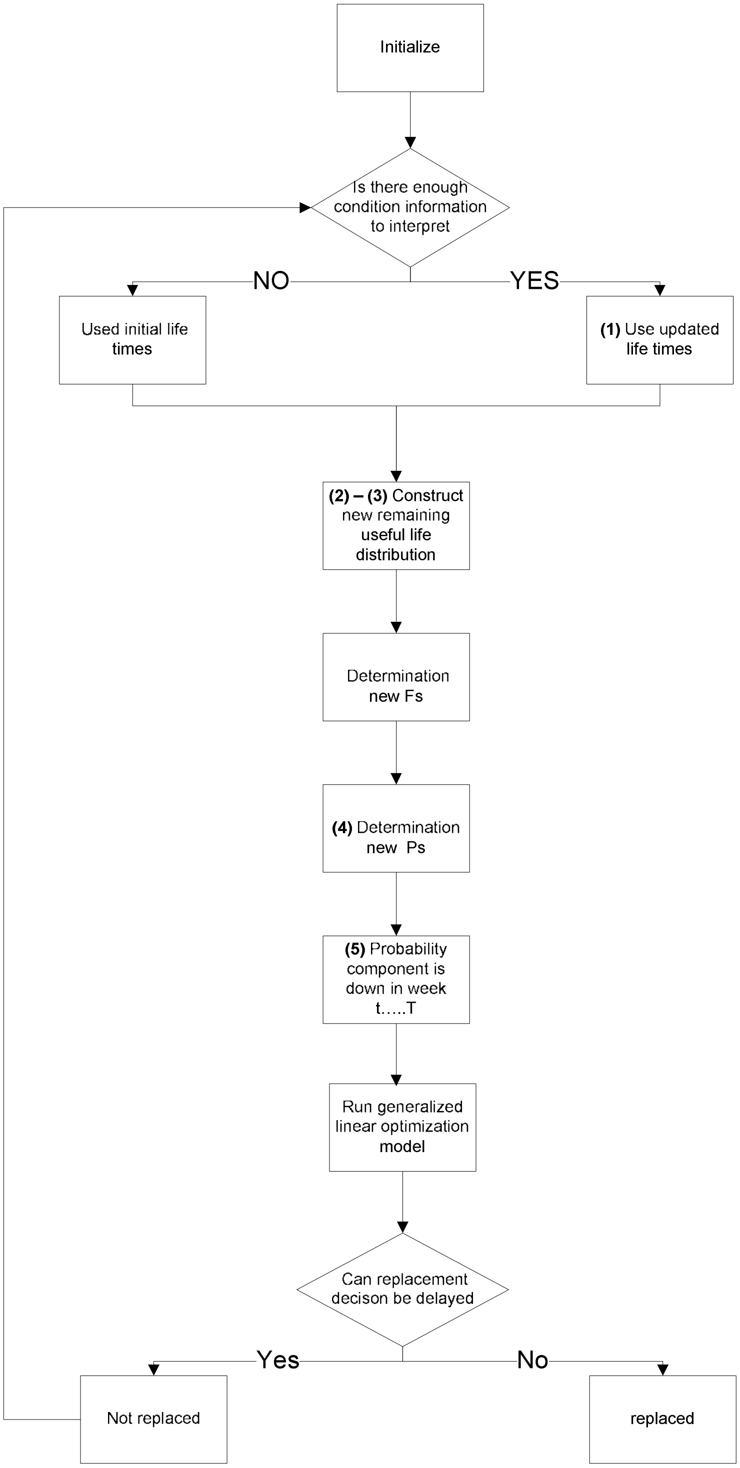

Figure 13 Steps undergone in CBM policy every decision time t

### 6.3.2. The MSPP policy

This policy is extensively discussed in chapter 2. A maintenance kit has a maximum replacement interval. Because the intervals can differ per maintenance kit, the maintenance kit with the minimum length interval determines the minimum visiting interval. The remaining maintenance kits are then clustered together based on the determined minimum visiting interval. The remaining kits are clustered such that their time between visits never exceeds their maximum replacement interval. Therefore this policy can be classified as a block policy. Hence, the preventive maintenance actions are set at times T, ..2T, ..3T,..., and apply corrective maintenance actions if a maintenance kit fails in between these set times.

### 6.3.3. The 95 % policy

A commonly used maintenance policy is that of determining the replacement interval based on historical data. If failure data is available on a large scale then it is possible to determine a 95 percentile that the component will not fail before a certain time on the long run. This means that on the long run only 5 percent of a certain maintenance kit will fail before a certain age. This age determines the replacement interval. It should be noted that this policy does not make use of any clustering. Therefore it is a tradeoff between assuring a reliability of 95 % per maintenance kit and therefore minimizing the expected downtime cost versus the increase of the shared fixed costs due to uncoordinated visits. This policy is chosen because it is a commonly used maintenance concept by companies due to its simplicity.

### 6.3.4. The frequency constraint clustering (FCC) policy

A basic clustering policy which can be used in combination with the individual replacement times, determined by the 95 % policy, is the clustering policy proposed by Dijkhuizen and van Harten (1997). They propose an optimal clustering method for frequency-constrained jobs with shared set-ups. Hence, their method is a good method to compare the effectiveness of a dynamic CBM policy compared to a static maintenance policy. This is especially so due to the incorporation of the shared fixed costs. The method used by Dijkhuizen and van Harten (1997) is explained in more detail in Appendix B.

## 6.4 Initially used data parameters

As mentioned the business case to compare the three different policies is based on a specific customer profile. This profile represents a high profile customer within the Western Europe region. To be able to compare the three maintenance policies the parameters described in chapter 5 are set based on the profile of such a customer. The assumed parameters are shown in Table 1. It must be noted that all parameters except the T(optimal) and ECC are independent of the initial expected degradation process. The T(optimal) is dependent on the initial expected degradation process and is computed according to the formulas shown in Appendix C.

**Table 1 Initial used parameters business case**

| Common parameters | | | | | |
|---|---|---|---|---|---|
| **FCM** | 2000 euro | | | | |
| **CDT** | 90000 euro p.h | | | | |
| **CMT** | 30 euro p.h | | | | |
| | | | | | |
| **Individual parameters** | C-Kit chain | C-Kit chain | C-Kit Gear Unit | D-Kit Gear Unit | C – Kit Transport |
| **EERT (hours)** | 0.5 | 1 | 2 | 1 | 0.5 |
| **CEU (euro)** | 1,876.41 | 1,946.69 | 1,952.39 | 3,628.9 | 1,246.64 |
| **T (optimal) (weeks)** | 14 | 24 | 11 | 5 | 6 |
| **ECC (euro)** | 67 | 43.37 | 99.35 | 107.84 | 23.84 |
| **ERT (hours)** | 2 | 2 | 3 | 5 | 2 |
| **CU (euro)** | 676.41 | 746.69 | 752.39 | 2,428.9 | 41.64 |

## 6.5 Policy performance based on different lifetime scenarios

In Paragraph 6.3 it is stated that there is no statistical data available at MSPP. Due to the missing data it would be beneficial to investigate how the different policies perform given different lifetime estimates. Therefore the performance of the defined policies will be explored considering different initial expected degradation processes. The different initial expected degradation processes of the assigned critical components therefore define the different scenarios. This will be described in paragraph 6.5.1. Subsequently, paragraph 6.5.2 discusses how the scenarios are processed such that the data needed as input for the performance measures is available. These performance measures are discussed in paragraph 6.5.3. After which paragraph 6.5.4 up to 6.5.6 discuss the results of the each scenario separately. Finally, the chapter ends with a conclusion in paragraph 6.5.7.

### 6.5.1. Scenario set-up

Based on the initial degradation process drawing described in paragraph 6.2, the initial expected lifetime, of each assigned critical component of the maintenance kits taken under consideration, are defined. Based on the drawings which are graphically shown in Appendix D a distribution is fitted.

Consequently, all critical components have been fitted as a Weibul distribution with a certain mean μ, a shape parameter α and the scale parameter β. The associated parameters to the fitted distribution which will serve as Scenario 1 are shown in Table 2. Additionally, Table 2 shows the time between replacement for the Marel Stork (MSPP) policy as well as that of the 95 % policy. The time between replacements is shown in weeks. Finally, Table 2 shows the time between replacements for the FCC policy. The time between replacements shown in Table 2 for the MSPP policy are the same for the other scenarios and will only be displayed in Table 2. This also applies to the shape parameter α assigned to the different maintenance kits. The fitting of the normal distribution to determine the time between replacements for the 95 % policy are shown in Appendix E. After which Appendix F presents the computations used to determine the time between replacements for the FCC policy used in scenario 1.

### *Scenario 1:*

**Table 2 Expected degradation process generated data scenario 1**

| Parameters | Maintenance kit | C – Kit Chain | D – Kit Chain | C – Kit Gear Unit | D – Kit Gear Unit | C – Kit Transport |
|---|---|---|---|---|---|---|
| μ | | 31 | 61 | 31 | 61 | 21 |
| α | | 4.77 | 4.60 | 4.77 | 4.60 | 4.29 |
| β | | 33.85 | 66.75 | 33.85 | 66.75 | 23.07 |
| MSPP policy | | 36 | 72 | 36 | 72 | 24 |
| 95 % policy | | 20 | 34 | 20 | 34 | 12 |
| FCC policy | | 12 | 34 | 12 | 34 | 12 |

The set-up of scenario 2 is similar as that of scenario 1. Scenario 2 also assumes that the life time degradation processes of the critical components follow a Weilbul process. The main difference between scenario 1 and 2 are the expected life times of the critical components. In scenario 2 it is assumed that the mean lifetimes of the critical components are larger than those fitted in the Scenario 1 with a factor of 1.5. The shape of the expected life time process is left intact. Therefore, the only unknown variable is that of the scale parameter. These are computed by formula 3 in paragraph 6.3.1. The parameters associated to the initial expected degradation process for Scenario 2 are shown in Table 3. Furthermore, the time between replacements for the 95 % policy are also shown in Table 3 whereas the fitting of the normal distribution to determine the 95 % policy is shown in Appendix G. Finally, Table 3 shows the time between replacements for the FCC policy of which the computations to determine these replacement times are shown in Appendix H.

### *Scenario 2:*

**Table 3 Expected degradation process generated data scenario 2**

| Parameters | Maintenance kit | C – Kit Chain | D – Kit Chain | C – Kit Gear Unit | D – Kit Gear Unit | C – Kit Transport |
|---|---|---|---|---|---|---|
| μ | | 46.5 | 91.5 | 46.5 | 91.5 | 31.5 |
| β | | 52.77 | 122.1289 | 52.7798 | 122.1289 | 34.6122 |
| 95 % policy | | 30 | 57 | 30 | 57 | 18 |
| FCC policy | | 18 | 57 | 18 | 57 | 18 |

The third and final scenario is the scenario where the mean of the critical components are twice as large as those fitted in Scenario 1. Scenario 3 also assumes that the shapes of the expected life times are identical to those fitted in Scenario 1. Therefore identical to Scenario 2 the scale parameter for each critical component is computed by formula 3 which is used in the CBM policy. Identical to Table 1 and Table 2, the last two rows in Table 3 show the time between replacements for the 95 % as well as the FCC policy. A more detailed explanation how these are determined is shown in Appendix I and Appendix J.

### *Scenario 3:*

**Table 4 Expected degradation process generated data scenario 3**

| Parameters | Maintenance kit | C – Kit Chain | D – Kit Chain | C – Kit Gear Unit | D – Kit Gear Unit | C – Kit Transport |
|---|---|---|---|---|---|---|
| μ | | 62 | 122 | 62 | 122 | 42 |
| β | | 67.70 | 133.50 | 67.70 | 133.50 | 46.14 |
| 95 % policy | | 37 | 68 | 37 | 68 | 24 |
| FCC policy | | 18 | 57 | 18 | 57 | 18 |

### 6.5.2. Framework scenario testing

The scenario testing is the iterative execution of the CBM policy per decision epoch t, described in paragraph 6.3.1, such as in a rolling horizon model. This is the same way it should be used in practice, described in paragraph 4.4.

The scenario starts with an initialization in which the data regarding the four different cost structures are implemented, these being; preventive maintenance, corrective maintenance, shared fixed costs and the cost of the remaining number of cycles. After which the real mean failure data for each component $s_i \in s$, where i states the version of the component that is in the system and $s \in S$, is generated. Each time component $s_i \in s$ is replaced a new component with the indicator i = i + 1 is generated and inserted. The mean life time of the component $s_i \in s$ is generated and is assumed to be Weibull distributed with a known shape parameter α. The generation of the mean life time of the component $s_i$ derived of the initial expected mean life time of component $s$ which is presented in paragraph 6.5.1. This random generation is used to model the real CDF of the components $s_i \in s$ mean life time, which are used in the scenario. This is shown in the following formula;

$$Mean\ life\ time\ (X)\ component\ s_i = E_{\mu_s}\left[E[X \mid \mu_s = i]\right]$$

The formula states that the mean life time of component $s_i \in s$ is a random variable which is based on the initial estimated mean life time, distribution and its mean ($\mu_s$ ), of the component $s \in S$. Given this methodology for generating the needed characteristics of the components the scenario can be run. The scenario starts at time t = 0 and then every period t the decision is made, for each component $s_i \in s$, if it should be replaced or not. If not replaced the component maintains in the system at least up to period t + 1. When decided to replace the component $s_i$ the replacement time is registered and a new expected failure time X for component $s_{i+1}$ is generated and implemented in the system in period t + 1.

Every time the decision is made to proceed to the next period (t + 1) a decision process occurs to check if t is larger than T. Variable T states the maximum number of time periods taken for the scenario testing. Once T is reached the scenario is completed.

### 6.5.3 Performance measures

To provide insights regarding the advantage or disadvantages of using the designed CBM policy it is important to determine a set of criteria on behalf of which the comparison can be made. These criteria's are called performance measures. To distinctively be able to provide insights regarding the exact behavior of the different policies three performance measures have been set. The following three performance measures are used;

- Average expected machine availability;
- Expected number of replacement kits needed;
- Total expected cost.

### *Expected machine availability*

In the previous paragraph is described that for every version i of component $s \in S$ a mean failure time is generated. Given the assumption that this failure time and its associated CDF are Weibull distributed, provides a known behavior for each version of each component kit. Given that the underlying degradation process for each version, its failure probabilities at each time t and the replacement times of each component are known the expected system availability ($A_t$) for that period t can then be computed as following;

$$A_t = \prod_{s=1}^{S} (1 - q_t^s)$$

Furthermore, we can derive the average expected machine availability once provided with the system availability for each period t and knowing the total time period T. The average expected maintenance availability is defined as following;

$$\text{Average expected maintenance availability} = \frac{\sum_{t=0}^{T} A_t}{T}$$

### *Expected number of replacement kits needed*

This performance measure shows the number of replacement kits needed during the total time units that the scenario is run.

### *Expected Total Cost*

The Expected Total Cost is a combination of the above two performance measures plus the inclusion of the shared fixed costs. Hence, the Expected Total Cost exits of three parts. There is the expected cost of downtime, the cost of the planned replacements per unit and finally there are the fixed cost assigned to each visit. This can be formulated as following;

$$\begin{aligned} &Expected\ Total\ Cost \\ &= \sum_{s=1}^{S} \left[ \sum_{t=1}^{T} \left( (q_t^s) \cdot downtime\ component\ s\ \cdot downtime\ cost \right) \right] + ENPM^s\ \cdot CPM^s \\ &+ \ the\ number\ of\ visits\ \cdot FCM \end{aligned}$$

This given that T is the total horizon of time periods t of which the scenario exits, $ENCM^s$ is the expected number of preventive maintenance visits executed within the time period T for each component s. Finally, $CPM^s$ is the cost of a preventive maintenance visit for component s.

### 6.5.4. Results performance measure Expected Availability

The performance measure Expected Availability was introduced to investigate how the CBM policy will compare with other policies providing the different initial expected mean lifetimes. Furthermore, the results will provide insights regarding the individual performance of each policy given the different initial expected mean lifetimes. Table 5 shows the average utilization for each policy for each scenario. Additionally, the relative performance compared with the other policies is presented beside the alternative policies per scenario. Furthermore, Figure 14 and Figure 15 present the availability graph during each time unit for the total scenario time. Scenario 1 and 3 are chosen because they are the most different of each other regarding the initial expected mean lifetime. Finally, Appendix K presents the Availability graphs of all the scenarios in a larger scale.

Table 5 Average Availability parameters and relative policy comparison

| Scenario | 1 | 2 | 3 |
|---|---|---|---|
| **Policy** | | | |
| **CBM Policy** | 99.0% | 98.83 % | 98.80 % |
| **Marel Stork Policy** | 94.2% | 96.34 % | 98.41 % |
| **95 % Policy** | 99.0% | 97.83 % | 98.40 % |
| **FCC Policy** | 99.4% | 98.6 % | 98.88 % |

Given the presented results in Table 5 it is able to conclude that if the initial expected mean lifetime is shorter than the time between replacements of the Marel Stork Policy, as in scenario 1, that the current policy used by MSPP performs the lowest of all policies. The less effectiveness of the policy used by MSPP is due to the rather long replacement interval used by MSPP if this initial expected mean lifetime would be accurate for the components in the system. It was expected that the 95 % policy which adjusts its replacement interval according to the initial expected mean lifetime would perform well regarding machine availability due to the very short and strict replacement intervals. Nevertheless, the results show that the CBM policy outperforms such a policy due to its ability to anticipate failures which occur much more sudden than expected. Nevertheless this policy does not consider the cost of visiting a facility. The outperformance of the CBM policy compared to the Marel Stork policy in scenario 1 is likewise logical. As the maximum time of replacement (threshold) was set at the mean time of failure (50 percent of failure), the CBM policy provides a more reliable policy.

Whereas the Marel Stork policy in this case sometimes replaces a component at a moment which would not be possible in the CBM policy.

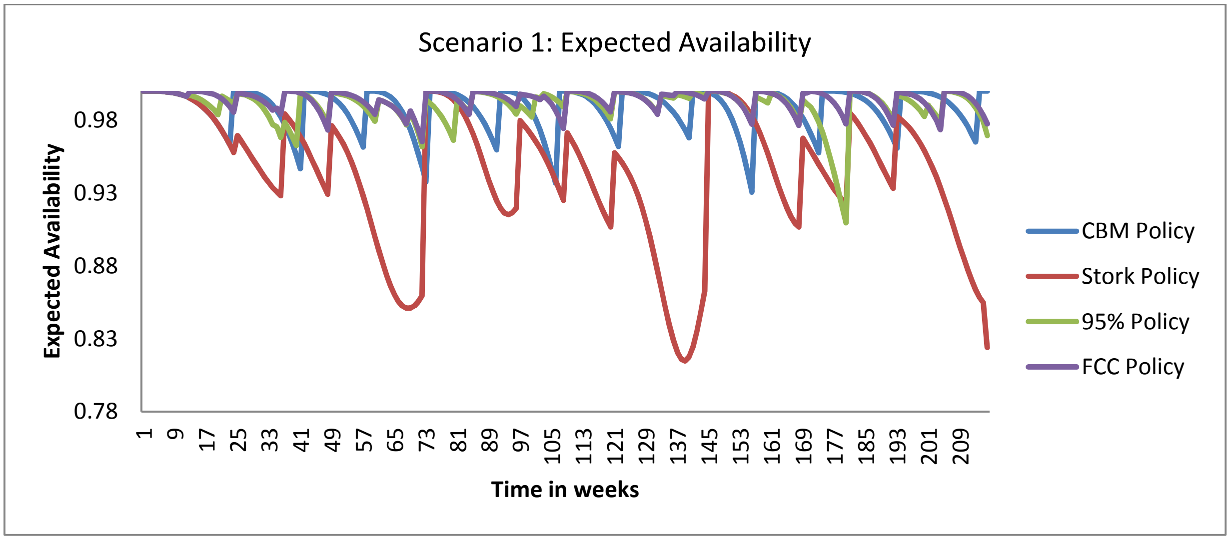

Figure 14 Results performance measure Availability scenario 1

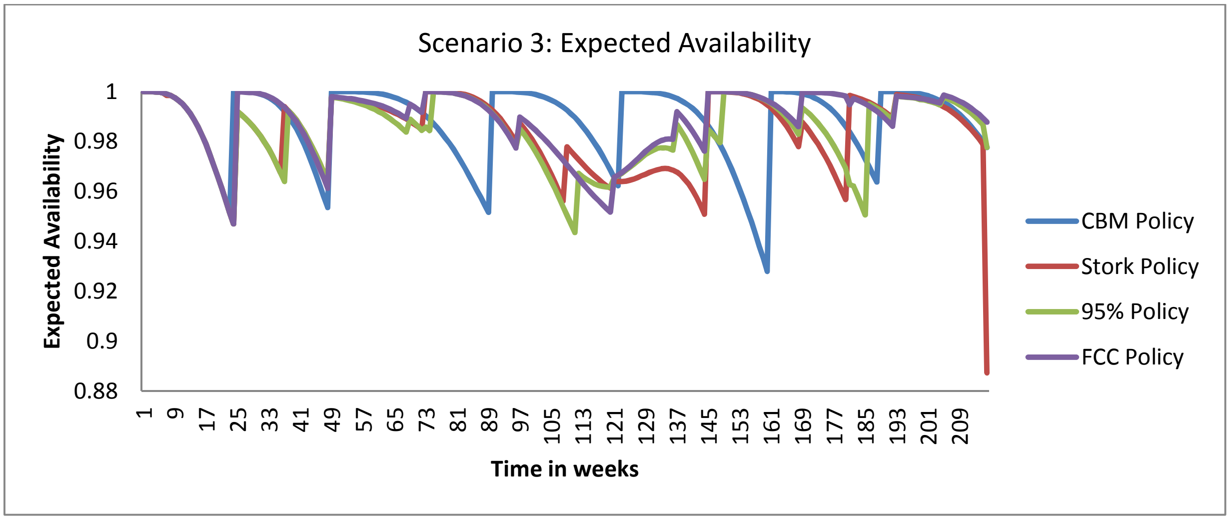

Figure 15  Results performance measure Availability scenario 3

Furthermore, the results in Table 5 show that if the initial expected mean lifetime, for each critical component in the maintenance kit, is twice that of the initial expected mean lifetimes determined in scenario 1 that the performance of the CBM policy still outperforms the Marel Stork and 95 % policies. Although in this case (Scenario 3) the relative difference in expected availability is between the different policies is decreasing compared to the other life time cases (Scenario 1 and 2). Additionally, it can be seen that the performance of the policy used by MSPP moves towards that of the 95 % policy. This difference can also be seen in Figure 14 and Figure 15.

Figure 15 shows that it is the CBM policy performs quite similar as the Marel Stork policy during the total scenario time. When analyzing Scenario 1 clearly it is the Marel Stork Policy that has the deepest peaks, shown in Figure 14. The behavior shown in Figure 15 is also represented in Table 5 by the averages shown regarding Scenario 3. That the Marel Stork policy performs similar to the CBM policy in Scenario 3 is because the Marel Stork policy has become a very conservative policy with relatively short replacement intervals compared to the initial expected mean lifetimes. The same reasoning also applies to the overall performance of the FCC policy.

### 6.5.5. Results performance measure Expected number of kits replaced

The performance measure Expected number of kits replaced was introduced to investigate how the CBM policy will increase or decrease the expected number of times that a maintenance kit is replaced compared to the other policies. Given the different initial expected mean lifetimes. Furthermore, the results are needed to explain the previous discussed results concerning the machine availability. The bar charts that graphically show the results of the different scenarios are all presented in Appendix L. To provide some insights the results of scenario 1 and 3 will be further discussed in this paragraph. These results are presented by Figure 16 and Figure 17.

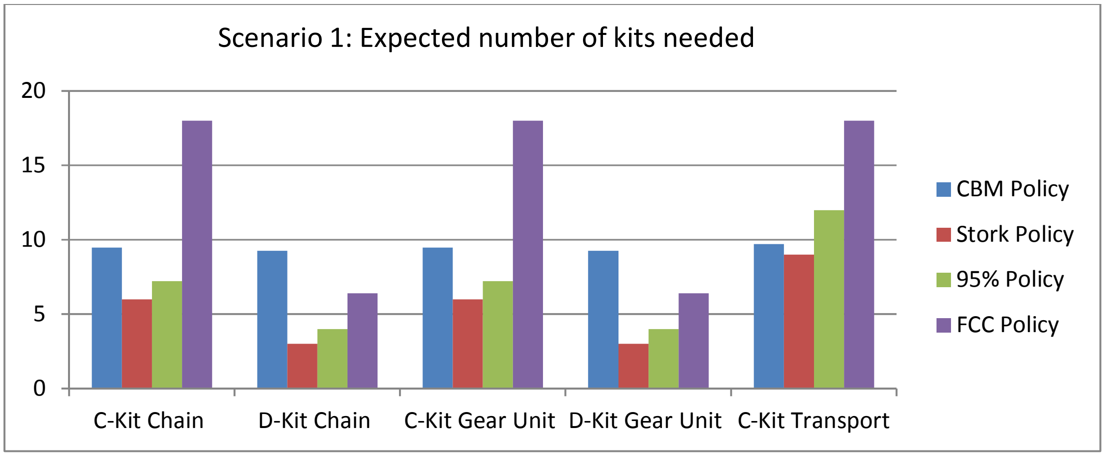

Figure 16 Results performance measure number of maintenance kits replaced scenario 1

The results of the performance measure provide several insights. At first we are able to conclude that the stricter the replacement rule, meaning the higher the probability of non-failure occurring based on the initial expected mean lifetime, the increase of the number of kits that are replaced. Intuitively this makes sense. The stricter the replacement rule, the smaller the replacement interval becomes and therefore increases the expected number of kits replaced. This phenomenon can be traced back to the above scenarios and can be identified in all policies.

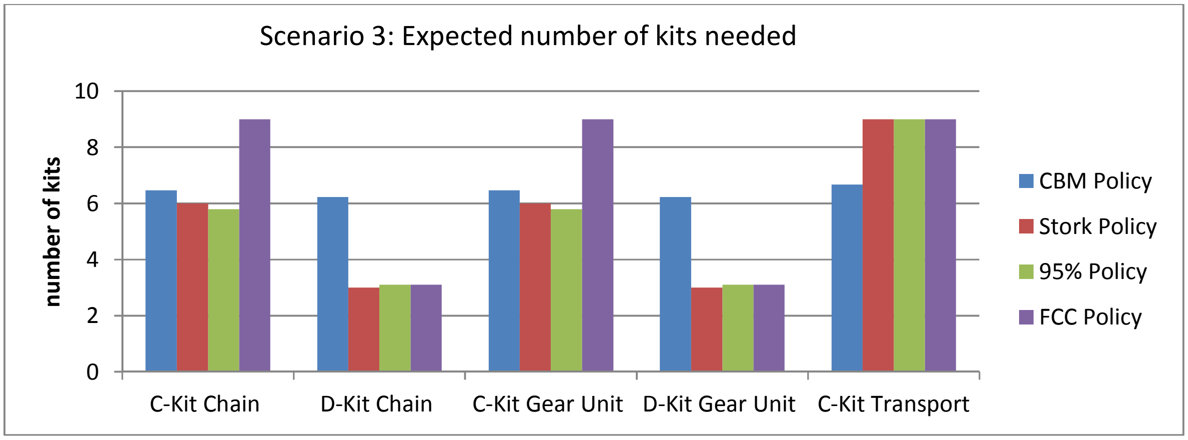

Figure 17 Results performance measure number of maintenance kits replaced scenario 3

The results show that the CBM policy in almost all cases replaces the largest amount of kits during the scenario analysis for all different sub-assemblies. Only, the FCC policy replaces the maintenance kits with short lifetimes more often. This is clearly seen in Scenario 1. In the opposite case projected in Scenario 3, the same conclusion still applies only here we see that the policy used by MSPP has also become very conservative. Hence, the number of kits used by the Marel Stork policy is similar to the other policies. Finally, the same kind of reasoning can be applied when analyzing the CBM policy. In Scenario 1 the CBM policy is stricter then the Marel Stork policy in spite of its relative non strict threshold levels and therefore executes more replacements that the Marel Stork policy. Due to the extremely high downtime and the relatively low shared fixed cost the policy generally replaced the maintenance kits near to the minimum allowable time of replacement. In Scenario 3 the CBM policy performed on average equal to the Marel Stork policy based on the average availability. Therefore, as expected the C-kits are replaced approximately the same amount of times, the D-kits are not.

Concluding that, given the rather non conservative threshold levels assumed as well as the extremely high corrective replacement cost (due to high downtime cost) compared to the preventive maintenance as well as the shared fixed cost, the advantage of the CBM policy concerning decreasing the Total Life Cycle Cost by less replacements becomes larger when the initial expected mean lifetime becomes larger.

### 6.5.6. Results performance measure Expected Total Cost

The performance measure Expected Total Cost translates the physical performance of the different policies into a financial statement. The performance measure Total cost is a combination of the above two performance measures and the number of visits which assigned the shared fixed costs. The availability performance is represented by the expected downtime cost. The performance measure expected number of kits needed influence the assignment of preventive maintenance costs.

Finally, there is the assignment of the total shared fixed costs which are assigned each maintenance visit.

The bar charts that graphically show the results of the different scenarios are all presented in Appendix M. To provide some insights the results of scenario 1 and 3 will be further discussed in this paragraph. These results are presented by Figure 19 and Figure 18. The bar charts present the total cost containing the above three elements. Furthermore, the bar charts also present the cost value assigned to the total cost due to the shared fixed costs.

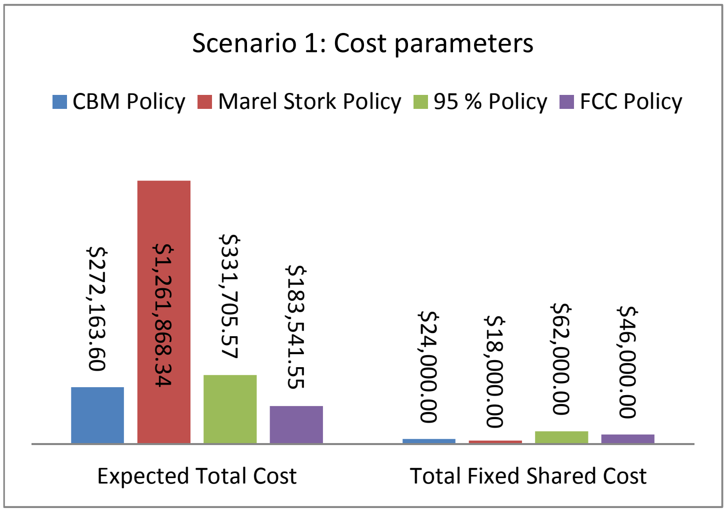

Figure 19 Results performance measure Expected Total Cost Scenario 1

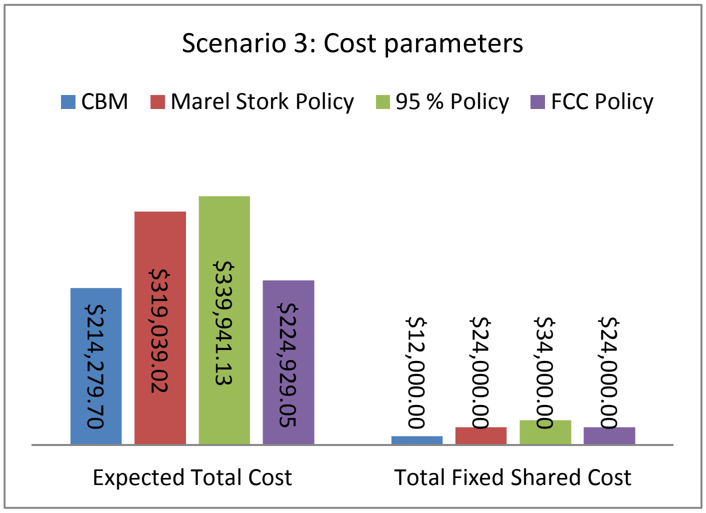

Figure 18 Results performance measure Expected Total Cost Scenario 3

Figure 18 and Figure 19 show that the extremely high downtime costs affect the expected total cost in such a way that this performance measure has the same behavior as the performance measure Expected Availability.

The extremely high downtime cost lead to the situation that the policy which increases the availability the most, performs the best in the minimization of the cost. For all three scenarios it can be seen that the Expected Shared Fixed Cost hardly contribute to the Expected Total Cost. Naturally, this was to be expected. Interesting to see is that in all cases the CBM policy performs better than the Marel Stork and 95 % policies. Additionally, the results concerning the expected costs show that in the situation where the policies have rather similar average availability performances that the CBM policy still outperforms the other policies by the minimization of the total shared fixed costs. Furthermore, the CBM policy replaces the D-Kits much more frequent then the other two policies. This is because the CBM policy makes a tradeoff between the risks of extending its life time, the gained economical advantage of using less maintenance kits and having to execute an additional visit with its associated fixed costs as a result.

Finally, the results show that the CBM policy does not always perform better then the FCC policy. The results of Scenario 1 clearly show that the advantage and the performance of the CBM policy depend on the form of the RUL lives which is available. The combination of the current RULs of the maintenance kits used and the one week replacement lead time led the CBM policy to delay the decision up to around three weeks after the time of the decision. Therefore, the CBM policy underperformed in some situations because the shape of the RUL was not accurate.

Concluding given the situation that the shared fixed cost are very low and the corrective maintenance cost are much higher than the preventive maintenance cost, the CBM policy outperforms the Marel Stork policy as well as the 95 % policy. Furthermore, the shape of the RUL and therefore the accurateness of the representation of the actual life times are of extreme importance. If the RUL distribution are not accurate over time the value of using CBM decreases and can in some situations be outperformed by more basic maintenance policies which make use of clustering.

## 6.5 Conclusion

The three scenarios provided insights regarding the performance of the CBM policy compared to the other two polices given different mean life times. The results show that if it is the case that the replacement time interval of the Marel Stork policy is larger (Scenario 1) or even slightly smaller (Scenario 2) then the mean life time of the critical components assigned to each maintenance kit then the CBM policy outperforms the Marel Stork policy. Hence, the CBM policy provides the possibility to anticipate the failures of components which are expected to fail prior to a fixed interval. These failures are not anticipated by the Marel Stork policy and therefore the policy performs less when compared on the performance measure Expected Availability as well as Expected Total Costs. Nevertheless, in Scenario 3 where the mean life times of the components are much larger than the replacement interval the CBM policy still outperforms the Marel Stork as well as the 95% policy. Only in this scenario the effect of minimizing the total shared fixed costs by the CBM policy becomes more important. The following three main conclusions can be made;

- First, there is still uncertainty what the effect would be of a more conservative failure threshold.
- Secondly, when optimizing based on expected cost, given the case settings for the high end market customers in Europe, it is of major importance to decrease the expected availability. This due to the extremely high downtime costs.

- For the above stated customer profile the extension of the lifetime and therefore decrease of the number of maintenance kits and effect of decrease the shared fixed cost hardly influence the expected costs.

The latter two of the above stated conclusions are given extra strength when evaluating the results concerning the CBM policy. In all three scenarios the CBM policy outperforms the 95 % policy as well as the Marel Stork policy. The high downtime costs compared to the relative cheap parts within each maintenance kit and shared fixed costs leads us to conclude that the use of a CBM policy is preferable.

The above stated conclusions provided evidence to further research the behavior and applicability of the proposed CBM policy in three different situations.

1. First, it is uncertain what the effect of a more conservative failure threshold will have on the performance of the CBM policy. Especially, in situations where the downtime costs (corrective maintenance costs) are much higher than the preventive maintenance and shared fixed costs. Therefore the policy should be tested with a more conservative failure threshold.
2. Secondly, would the performance of the CBM policy underperform, based on the expected costs, if the corrective maintenance costs would not be so high compared to the other costs? This is a relevant question which could identify the applicability of the policy to other customer profiles.
3. Finally, would the performance of the CBM policy be the same compared to the other two policies if the shared fixed costs would increase?

The scenarios which can provide some clarity regarding the above three questions are discussed in the next chapter.

# 6. Application Condition based maintenance: Sensitivity

The conclusion in Chapter 5 discusses the need for further research regarding the performance of the CBM policy compared to the Marel Stork and 95 % policy. Because Scenario 3 was the only scenario where the CBM policy performed the poorest, this chapter will assume the lifetimes and further data assumptions used in Scenario 3 if not stated otherwise. The first concern was the setting of the failure threshold. Therefore this chapter will explore the behavior of the CBM policy with a more conservative failure threshold. This matter is addressed in paragraph 6.1 Furthermore, it was concluded that the assumption made regarding height of the corrective maintenance cost had a large impact on when which policy would be more beneficial. Therefore paragraph 6.2 will provide insights regarding the performance with a different corrective maintenance cost. Finally, paragraph 6.3 will address the effect of the shared fixed costs on the performance of the CBM policy compared to the other policies.

## 6.1. CBM policy: a 95 % reliability failure threshold.

Chapter 5 concluded that the original assumption made concerning the failure threshold (maximum replacement time), which is derived from the RUL, was to progressive to obtain good results compared to the other two policies when the expected lifetimes were much longer then the fixed replacement intervals used by the Marel Stork. Therefore Scenario 3 applied in Chapter 5 is executed again with the following additional assumptions.

- The failure threshold defined as the maximum replacement time for each maintenance kit is the time at which the cumulative failure probability is 5 %. This 5 % is based on the RUL distribution which is generated each decision epoch t for each maintenance kit.

### 6.1.1. Results Performance measures

The newly implemented rules regarding the maximum replacement times have led to no changes or improvement of the CBM policy when compared to the other two policies. In fact the results of the CBM policy are exactly the same as they were when using a progressive failure threshold. Therefore, in the current situation where the downtime costs are so extremely high compared with the units costs as well as the shared fixed costs the determination of the failure threshold becomes less important.

It makes sense that an individual threshold of 95% reliability does not affect the performance of the CBM policy given the current cost structure. Given that the average system availability is 98.8 % and therefore meaning that the average individual maintenance kit availability is even higher than 98.8

%. Therefore, an individual failure threshold would need to be extremely high if it should affect the CBM policy given the current cost structure. This seems rather unnecessary as the model in currently finds the optimal solution based on expected costs and is not constrained by any prior determined parameters.

## 6.2. Scenario: low corrective maintenance costs

Furthermore, Chapter 5 concluded that the extremely high downtime costs provided a situation in which a CBM policy does not naturally have to be the best option. Therefore this paragraph will provide insights regarding how the CBM policy would compare if it would be applied in situations where the downtime costs are not as large as is the case for the high end market customers previously modeled. The scenario will be based on the same assumptions made in paragraph 6.1 concerning the minimum and maximum replacement time of each maintenance kit. Further, the corrective maintenance costs have been lowered by lowering the downtime costs per hour from 90.000 euro per hour to 9.000 euro per hour.

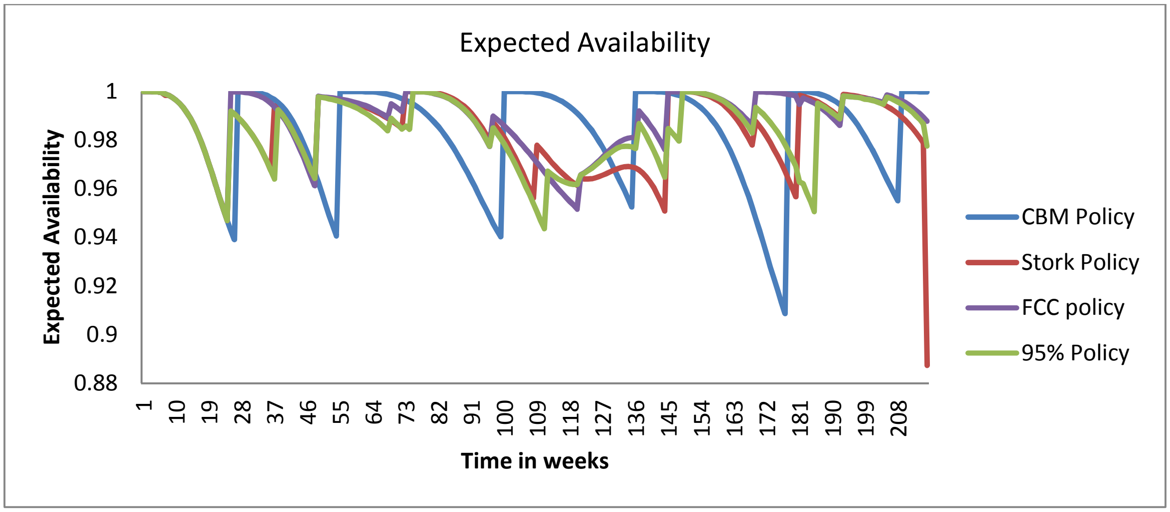

Figure 20 Expected availability per period scenario with low downtime costs

Figure 20 shows that regarding the availability per period it is the CBM policy which shows low peaks regarding the availability at certain times. Nevertheless the effects of these low peaks have decreased considerably as is shown in Figure 21.

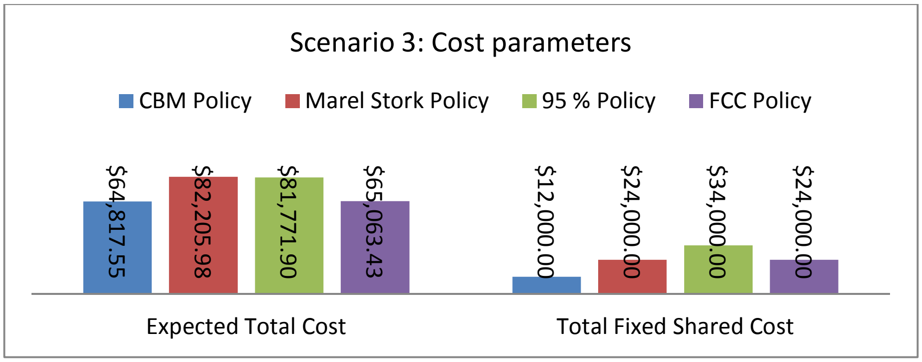

Figure 21 Results performance measure Expected Total Cost for the scenario: low downtime costs decrease factor 10

In this case the effect of postponement is much less dramatic concerning the expected total costs. Given the assumption of the low downtime costs we see that the conservative policies Marel Stork and 95 % policy are outperformed. With low downtime costs compared to the costs of the maintenance kits and the shared fixed costs it becomes more beneficial to delay the maintenance replacement. This can be in the expected number of maintenance kits used, which is shown Appendix O. Hence, the fact that less maintenance kits are used shows that the model delays the replacement of maintenance kits longer compared with the initial situation.

Furthermore, it is concluded that the performance of the CBM policy compared to the FCC policy remains unchanged. Still the CBM policy outperforms the FCC policy although the difference is minimum. Nevertheless, as previously discussed the assumed shape of the RUL also effects the performance of the CBM policy.

In the case of low downtime the CBM policy keeps searching for optimal clustering opportunities. The policy clusters as much as it can given maximum replacement times. This because the corrective maintenance costs are much lower now and the risk of the sub-assembly failing becomes more acceptable. Hence, if relatively speaking the corrective maintenance costs decrease compared to the other costs, the impact on the expected total costs of the expected number of maintenance kits needed during the total life cycle, increases. Therefore, the minimization of the number of needed visits becomes very important.

## 6.3. Scenario: High shared fixed costs

Chapter 5 ended with the conclusion that the CBM policy would perform better, the larger the shared fixed costs are, relatively speaking. This is expected due to the fact that then the shared fixed costs have a relatively larger impact on the total expected costs. As this will be the case, the fact that CBM finds optimal solutions for spreading the fixed costs, whereas a conservative policy such as the 95 % policy does not. Therefore this paragraph will provide insights regarding the performance of the CBM policy if it would be applied in situations where the shared fixed costs are larger then was the case in Scenario 3 in Chapter 5, or in paragraph 6.1. The scenario will be based on the same assumptions made in paragraph 6.1 concerning the maximum replacement time of each maintenance kit. Further, the shared fixed costs have been increased from 2000 euro per visit up to 20.000 and 40.000 euro per visit and . Finally, the Marel Stork and 95 % policy remain unaffected by the change in the shared fixed costs whereas the FCC policy is affected. The adjusted FCC policy is shown in Table 6 with the according computations which determined this policy shown in Appendix P. The FCC policy remained the same regardless if the change in fixed costs was either 20.000 or 40.000 euro.

Table 6 Replacement time interval FCC policy

| Maintenance kit | 10 C | 10 D | 12 C | 12 D | 14 C |
|---|---|---|---|---|---|
| Replacement interval (weeks) | 24 | 24 | 24 | 24 | 24 |

The increase of the shared fixed costs had a positive effect on the performance of the CBM policy compared to the Marel Stork and 95 % polices. The increase in shared fixed costs scenario provided the following performance when evaluated based on the expected total costs. The results are shown in Figure 22 and Figure 23.

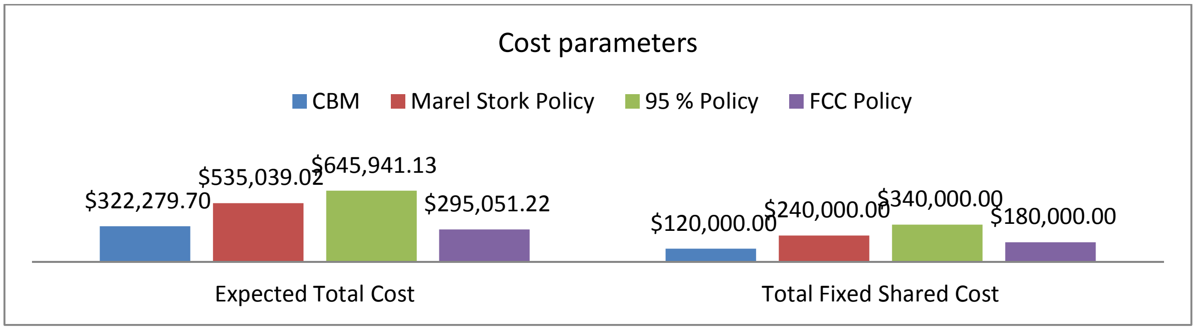

Figure 22 Results performance measure Expected Total Cost for the scenario: shared fixed costs increase with factor 10

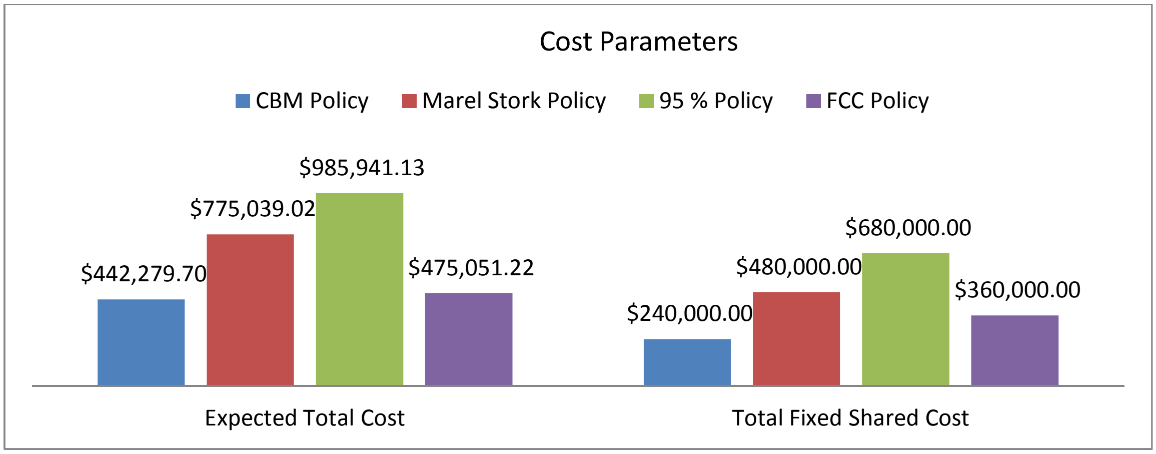

**Figure 23 Results performance measure Expected Total Cost for the scenario: shared fixed costs increase with factor 20**

The overall expected total costs have increased drastically which is expected. Interesting is that the increase of the shared fixed costs had no influence on the time of replacement of the maintenance kits when applying the CBM policy. It only influences the total expected costs. This is due to the affect of the minimization of the number of visits has increased. In this scenario we see that the 95 % policy is outperformed by the CBM policy as well as the Marel Stork policy. Hence, the high reliability concerning the expected downtime does not compensate the more frequent and uncoordinated visits anymore.

Finally, there is an interesting dynamic when comparing the CBM policy with the FCC policy. The increase in fixed costs resulted in a change in time between replacements when applying the FCC policy. All replacements are now executed simultaneously when applying the FCC policy. When the fixed costs are increased with a factor 10 the FCC policy outperforms the CBM policy. This is due to a combination of two factors. First, the increase of the fixed costs has led the FCC policy to be very conservative which provides a relative low expected downtime costs. Furthermore, the decrease of the expected downtime is so efficient that it compensates the increase of the shared fixed costs. Nevertheless, when increasing the shared fixed costs with a factor 20 we see that the CBM policy outperforms the FCC policy. Hence, the decrease in expected downtime cost by replacing more and more conservative does not compensate the increase in shared fixed costs anymore. Nevertheless, the above again illustrates that when the components RULs are not represented accurately and aggressively enough, especially in the beginning of the RUL as time goes by, the CBM policy losses its advantage.

# 7. Conclusions & Recommendations

In line with the current view of Oliva and Kallenberg (2003), that Original Equipment Manufacturers (OEM) are moving up the so-called service continuum, MSPP is orientating itself on this future steps. An important factor in moving up in the service continuum is the improvement and active participation of the OEM-er in the after-sales service. An essential aspect of improving the after-sales service is providing the customers with a good maintenance concept. Moving up the service continuum is not always a blessing for an OEM-er. It means more responsibility and therefore higher risks if these new responsibilities cannot be managed well. To have more grip on the extra responsibilities and higher client demands OEM-ers are rediscovering the phenomena of CBM as maintenance concept. Therefore, this master thesis developed a CBM framework which will explain how MSPP can further optimize their maintenance scheduling by using condition monitoring. Therefore the aim of the research was to answer the following research question:

*"How can the preventive maintenance practices for a multiple component system include components subject to condition monitoring and therefore decrease the total life cycle cost, taking into consideration the economic dependence of the maintenance jobs? "*

When taking CBM under consideration as a possible maintenance policy there are two main questions that must be answered, these are;

1. Is it technically feasible that condition monitoring will detect a gradual loss of the Function of the unit which would be subjected to condition monitoring;
2. Is it economically feasible that condition monitoring will detect a gradual loss of the Function of the unit which would be subjected to condition monitoring;

## 7.1. Conclusions

In this part the conclusions regarding the technical feasibility constraints, which are defined as the necessary pre-conditions will be discussed. After which the conclusions regarding the application of the different maintenance concepts will be discussed, under the heading "economic feasibility".

### 7.1.1. Technical feasibility

From a technical point of view to make condition monitoring possible several limiting conditions must be satisfied. The limiting conditions are;

- Each unit for which the maintenance decision should be made at least one trigger / critical part must be assigned which will determine the time of replacement for the whole unit.

- For each trigger part it must be possible to detect a possible failure which prohibits the unit in question to perform its desired function by a soft fault. A soft fault is a fault which developed gradually with time.
- For each soft fault assigned to a trigger part it must be possible to divide the degradation process over time into two phases. A so-called “useful life” and “wear out” phase must be determined. The “useful life” of a component is from the point in time that the unit is installed up to the point in time that, when using some form of predictive technology, one can first detect resistance to failure. Therefore, there must be an identifiable condition which indicates that a possible failure, which prohibits the unit in question to perform its desired function, is about to occur or in the process of occurring. The “wear out” phase starts where the “useful life” ends up to the point which is identified as a failure point. Therefore, it must be able to identify an identifiable condition which indicates when the component can be considered as failed.
- Finally, when applying condition monitoring techniques for maintenance purposes the time between the identifiable conditions which determine the start of the “wear out” phase and the end of it must be larger than the time between the maintenance decision-making.

### 7.1.2. Economic feasibility

Determining the economic feasibility of applying CBM for a multi-unit system is a rather complex phenomenon for which no answer is provided in the academic literature. Due to the interactions through shared costs and the non-identical character of the units in questions it would make the most sense to validate the feasibility based on a designed CBM strategy. Hence, to evaluate the added value of implementing a CBM policy, a planning and replacement strategy is developed such that this can be evaluated.

Based on the designed CBM policy and associated mathematical model several essential conclusions can be made for MSPP and OEM’s in general. These conclusions are based on the evaluation of the results given different: initial expected lifetimes, failure thresholds per trigger component and cost structures.

- The scenarios tests with different initial mean life times of the trigger parts showed that if the replacement time interval of the Marel Stork policy is larger or smaller than the initial mean life time then the CBM policy outperforms the Marel Stork policy. This is because the CBM policy anticipates failures which occur prior to the fixed replacement interval times used by the Marel Stork policy.

- The shape of the trigger parts cumulative distribution function does influence the performance of the CBM policy when it is compared to more traditional and especially conservative policies. Nevertheless, the influence is not as strong as the ratios between the different costs. This because if the cumulative distribution increases drastically in the beginning of the life time or later on in the life time of the component still a very conservative policy will outperform the CBM policy if the cost structure is such that the corrective maintenance costs are much higher the preventive as well as the shared fixed costs.
- The shape of the RUL used in the model each decision epoch does influence the performance of the CBM policy extremely. Especially, if the shape of the RUL does not increase aggressive enough in the beginning of the RUL distribution as the trigger parts become older. If this is the case the replacement times are delayed which has a negative effect on the expected total costs.
- If the corrective maintenance costs are extremely high, due to the downtime costs, compared to the preventive as well as the shared fixed costs then the added value of a CBM increases compared to a simple and conservative maintenance policy. This is because the CBM policy proactively anticipates the changes in the expected life time and therefore manages the expected downtime costs better. The larger the penalties are for an unexpected failure the larger the relative benefit is of using the CBM policy, compared to the Marel Stork as well as the 95 % policy, when comparing the results of the total expected costs.
- If the corrective maintenance costs are extremely high, due to the downtime costs, compared to the preventive as well as the shared fixed costs then the effect of the individual failure threshold, in the form of a reliability percentage, decreases. The high downtime costs cause the CBM policy to replace very conservatively. Hence, the higher the downtime costs the less the effect of individual failure threshold.
- Furthermore, another situation where the CBM policy is beneficial is, when the downtime times are relatively low. This is quite surprising as the literature, mainly focused on single item CBM policies, suggest that when there are high downtime costs a CBM policy should be considered. Nevertheless, when a multi-item maintenance policy in this situation the added value of the CBM policy is finding an optimal number of replacement visits needed and by extending the life time of the different maintenance kits.
- A different situation where a multi-item policy would be beneficial is when the ratio between the shared fixed costs and the variable costs are high. This meaning that the shared costs are relatively high compared to the other costs. In this case the CBM policy clearly outperformed

the other two conservative polices because the minimization of the expected number of visits began to become really profitable.

- The difference between the policy used by MSPP and the designed 95 % policy is that when the clustering of the maintenance actions is very important or the shared fixed costs are very high then the policy used by Marel Stork is beneficial to apply. If the clients downtime costs are extremely high compared to the costs of preventive maintenance as well as the shared fixed costs it could be considered to apply a very conservative maintenance policy which does not involve clustering. Then for these customers the best policy can be chosen when minimizing the expected total costs is the goal.

## 7.2. Recommendations

In this paragraph a short summation will be made regarding the maintenance practices at Marel Stork itself.

- The results provided by the scenario testing show that the current maintenance concept used by MSPP performs worse than the alternative proposed concepts. The main disadvantage of the currently used concept is that it is solely based on the engineers interpretation of the failure character of the critical components. Therefore, it is a relatively subjective and basically on the long term an unreliable way of defining the maintenance plan. The unreliability on the long term is partially due to the dependency on a few key employees within the company which define these maintenance concepts. This kind of subjective manner of constructing the maintenance policy provides no clear methodology, in the case new machines are introduced or the key employees leave the company. Therefore, it is not only based on costs aspects that it is advised to use one of the alternative methods. They also provide a more structural approach to setting up a maintenance policy such that the maintenance department is less dependent on several key employees.
- Furthermore, the scenarios clearly showed that the CBM policy can help Marel Stork to minimize the total costs of maintenance. Nevertheless, the real advantage of CBM for Marel Stork is depended on several factors. If it is possible for Marel Stork to gather the right information such that a clear prediction becomes possible the CBM policy provides Marel Stork a major advantage in decreasing the expected downtime costs and the minimization of the costs gained by executing a visit. If the prediction is less accurate the constructed FCC policy could be a good initiative. This policy would lead to a less subjective manner of

constructing the maintenance policy and would acquire less an investment to gather the necessary information.

- Other organizational aspects can be of concern besides the minimization of the expected costs when evaluating which maintenance policy to consider. One thing all the scenarios showed was that the CBM policy minimized the expected shared fixed costs. Hence, the CBM policy found an optimal way how to keep the utilization of the machinery high and simultaneously doing this with minimal necessary visits (overhauls). Therefore, the CBM policy would be of great advantage for Marel Stork if their clients would start demanding that Marel Stork starts minimizing their number of visits.
- Finally, how realistic is the possibility of installing the CBM policy within Marel Stork on a large scale. This is more a technical question then a logistical one. From a logistical point of view it clearly is possible for Marel Stork to be more proactive and use the CBM policy to determine the times to execute the maintenance visits. Therefore, it is recommended to start a clear research project how the necessary information, which is explained in this report, can be extracted from the machinery. After which, a more clear analysis can be made regarding the exact advantageous regarding the CBM policy.

# 8. Implementation

In this chapter the implementation of the proposed CBM policy are discussed. This chapter will discuss which steps are necessary such that a more accurate and precise evaluation can be made regarding the benefits of the proposed CBM policy. After which the implementation of the developed tool will shortly be discussed.

## 8.1. Recommendations

This project has indicated numerous pre-conditions which are necessary to be able to implement Condition-Based Maintenance. Therefore, to be able to make use of the designed policy MSPP should first research several matters. When considering a machine to be subjected to a CBM policy;

- The current maintenance kits composition which the sub-assemblies are divided into must be re-categorized such that every sub-assembly only contains maintenance kits which exist of the same coded spare parts.
- The possibility of assigning each maintenance kit one single trigger part which must be investigated. It is necessary that the failure assigned to this critical part can be identified by a certain degradation process. This degradation process must gradually develop with time.
- Important in Condition-Based Maintenance is data collection. Once the above two recommendations are fulfilled MSPP must start gathering data. The gathered data can then be investigated such that the best possible way to use this data to be able to predict a RUL can be identified.
- The analysis of the data and its conversion to a RUL is essential. MSPP must investigate if the data confirms that it is possible to differentiate between the “useful” life and the “wear out” phase.
- If the above is possible MSPP it must be confirmed if the time between detection of the start of the “wear out” phase up to the time of failure is longer than the time between each possible replacement decisions. Of this is not the case the application is not suitable to subject to the designed CBM policy.
- The scenario testing showed that the impact of the CBM policy is very dependent on the accuracy of the RUL. This means that if the RUL does not provide an accurate reflection of the real life time each time it is updated then the added value decreases. Therefore it is extremely important to test the RUL life updates in the constructed optimization model.
- The results further showed that the shape of the RUL has an impact of the optimization model. If the shape of the RUL does not change in an increasing way in time the danger is

that the RUL does not represent the real wear accurately and that therefore the CBM policy will delay the replacement longer then possible (or should). In that case more easy to implement policies such as the FCC policy could outperform the CBM policy. Therefore. MSPP should model the RULs after the data is gathered and implement it in the developed tool to evaluate the results.

## 8.2. Software

For the implementation of the CBM policy two software packages have been used. The main planning tool has been coded in Opensolver software. Opensolver is an Excel VBA add-in that extents Excel’s built-in Solver with a powerful and reliable solver. This software allows to have inputs from a excel spreadsheet such that the planning model can be solved in the same Excel file. Therefore the outputs are exported to another excel spreadsheet in the same file.

The second software used is Matlab. Matlab is used to compute the individual optimal age policy which is one of the input variables of the planning model. Matlab was used as it provided a built-in command such that it was possible to evaluate the incomplete Gamma function. This was used to compute the expected life time of a component which had a Weibul distributed life time. This is normally done by an integral from 0 to t but the complexity of the integral is such that it must be evaluated by and Incomplete Gamma function.

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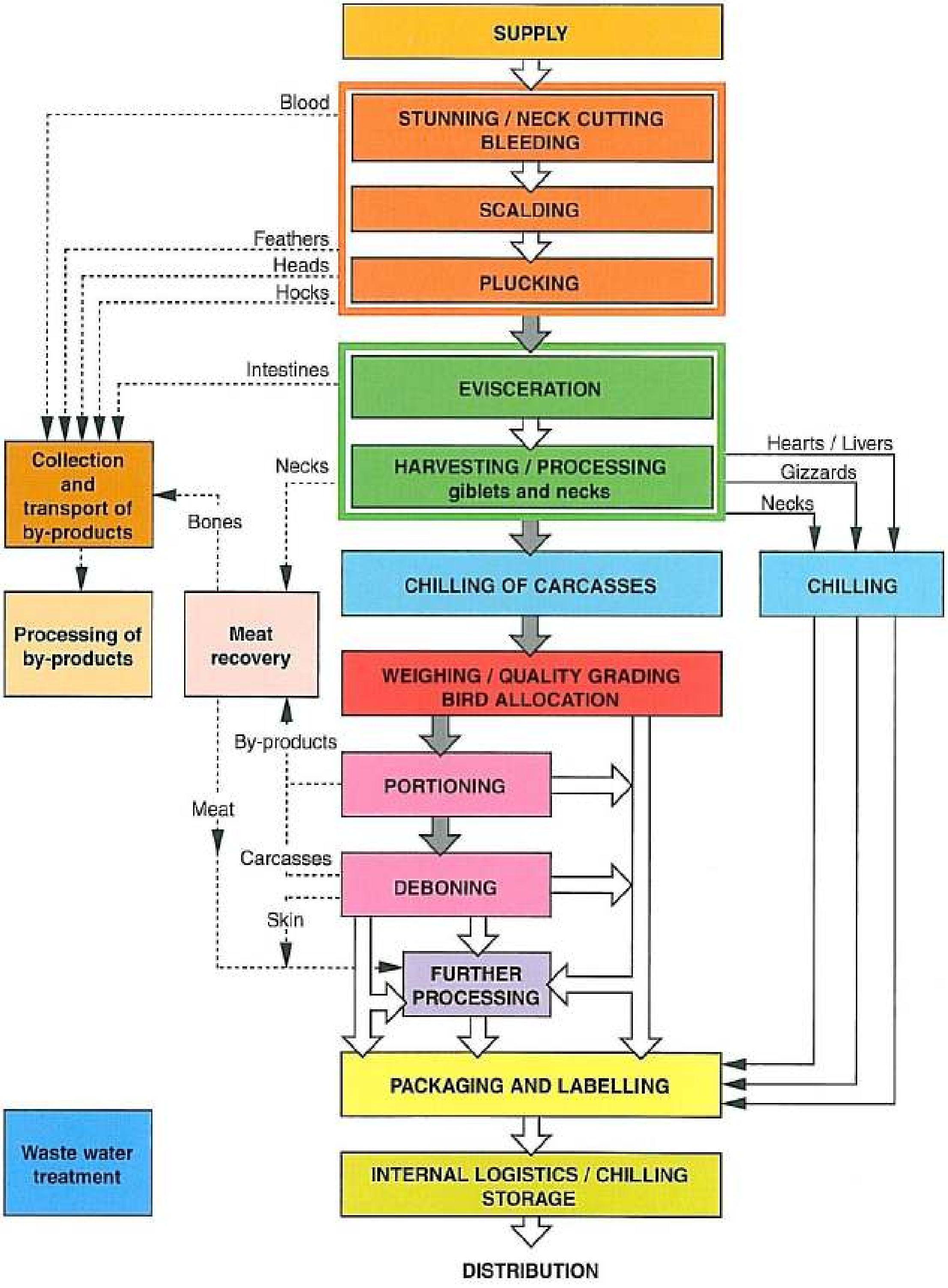
# Appendix A Complete poultry processing system



# Appendix B Clustering method by Dijkhuizen and van Harten (1997)

The fourth and final maintenance policy is the FCC policy. This policy is introduced such that the CBM policy as well as the Marel Stork policy can be compared with one more replacement policy which makes use of a clustering mechanism. The FCC policy is a combination of the individual determined replacement intervals based on the 95 % reliability and the clustering method proposed by Dijkhuizen and van Harten (1997) for frequency constraint maintenance jobs. The frequency which determines the frequency constraints for each maintenance kit is determined by converting the replacement intervals into number of visits per time interval.

## The clustering Model

Definition variables:

- n: Number of frequency constrained maintenance kits
- S =$\{1, \ldots\ldots, n\}$: Set of maintenance kits
- FCM: Shared fixed costs $(> 0)$
- $t_i$: Costs for replacing maintenance kit $i \in S$ $(> 0)$
- $f_i$ Limitative frequency of maintenance kit $i \in S$ $(> 0)$
- U: A cluster of maintenance kits which is a subset of $U \subseteq S$
- $f(U)$: Frequency of maintenance cluster U.
- $FCM(U)$: Shared fixed costs assigned to a cluster $U \subseteq S$
- $t(U)$: The maintenance costs assigned to a cluster $U \subseteq S$

Given the above the costs per time unit $\lambda(U)$ associated with U are defined as:

$$\lambda(U) = f(U)(FCM(U) + t(U))$$

The frequency $f(U)$ of a cluster of maintenance kits $U \subseteq S$ must be at least as high as the frequency $f_i$ of each maintenance kit $i \in U$. From a cost optimal point of view, it's obtained that:

$$f(U) = \max_{i\in U} f_i$$

The set-up costs $FCM(U)$ of a cluster $U \subseteq S$ depend on the collection of set-ups needed for all maintenance kits $i \in U$. Hence, $FCM(U)$ is given by:

$$FCM(U) = \sum_{i \in \cup_{i\in U} I_j} FCM_i$$

Obviously, the maintenance costs $t(U)$ assigned to a cluster $U \subseteq S$ are defined as:

$$t(U) = \sum_{i\in U} t_i$$

A clustering of maintenance kits is defined as a partitioning $\Omega$ of S. Since the objective is to minimize total costs per unit time, the goal is the clustering $\Omega^*$ which minimizes:

$$\Lambda(\Omega) = \sum_{\mathrm{U} \in \Omega} \lambda(U) = \sum_{\mathrm{U} \in \Omega} f(U)(FCM(U) + t(U))$$

## A dynamic programming algorithm

According to Dijhuizen and van Harten (1997) the clustering of maintenance jobs with, so called identical shared fixed costs, several dominance rules are provided. Three dominance rules are used in an efficient dynamic programming algorithm which solves the problem in a polynomial time.

Based on the following three properties the dynamic the dynamic programming algorithm van be applied;

i. It is never optimal to have two different clusters with the same frequency;
ii. For two maintenance jobs j and k with $\mathrm{f_j} \geq \mathrm{f_k}$ , it is never optimal to have j in a cluster with a lower frequency than the cluster of k.
iii. It is never optimal for a maintenance job j to be in a cluster with a frequency larger then
$$\frac{\mathrm{f_j}\left(\mathrm{FCM} + \mathrm{t_j}\right)}{\mathrm{t_j}}$$

When taking the above three properties into account and the maintenance jobs are ordered such that $\mathrm{f_1} \geq \mathrm{f_2} \geq \ldots \geq \mathrm{f_n}$ , then only clusters $\Omega$ of the form $\Omega = \{\{1, \ldots., \mathrm{k_1}\}, \{\mathrm{k_1} + 1, \ldots., \mathrm{k_2}\}, \{\mathrm{k_2} +$ 1,….,k3,…., with $1$<k1<k2<k3… , can be optimal.

Finally, based on the above stated properties Dijkhuizen and van Harten (1997) determined programming equation to compute F (k), which denotes the minimal costs for clustering jobs 1,….,k $(1 \leq k \leq n)$;

$$F(k) = \min_{1 \leq i \leq k : f_i \leq f_{max}^k} \left\{ F(i-1) + f_i \cdot \left( FCM + \sum_{j=1}^{k} t_j \right) \right\}$$

# Appendix C  Optimal Age Policy Maintenance kit

To determine the optimal age policy per maintenance kit we refer to Liu and Rad (2008). In according with Jardine and Tsang (2006), Liu and Rad (2008) defined the objective of the age policy determine the optimal preventive replacement interval for the system to minimize the total expected cost per unit time. Furthermore, it is assumed that the probability density function of the failure times can be derived from the initial expected failure behavior as described in paragraph 6.2. Therefore, it is assumed that the failure times are Weibull distributed.

## Age Replacement model

Definition variables:

- $C_p$ is the total cost of one preventive replacement.
- $C_f$ is the total cost of one failure replacement
- f(t) is the probability density function of the failure times of the system.
- t is the specified age at which a preventive replacement is performed.
- α is the shape parameter of Weibull distribution
- β is the scale parameter of Weibull distribution
- α , β are positive integers
- Note that it is assumed that the cost of downtime associated with mean time to repair data is included in $C_f$

The objective is to find the optimal replacement interval in order to minimize ERCTU (t). The function ERCTU (t) is the average cost per time unit for age replacement model as a function of t, where t is the predetermined time interval for each maintenance.

$$ERCTU(t) = \frac{C_p \cdot [1 - F(t)] + C_f \cdot F(t)}{\int_0^t [1 - F(u)]\, du} \qquad \textbf{Equation 1}$$

## Determining the Optimal Replacement Interval for the Age Replacement Model

The first step in determining the optimal replacement time interval t is to take the derivative of the cost function ERCTU(t) and set it equal to zero as follows:

$$ERCTU'(t) = \frac{-\left[C_p \cdot [1 - F(t)] + C_f \cdot F(t)\right] \cdot [1 - F(t)] + \left[-C_p \cdot f(t) + C_f \cdot f(t)\right] \cdot \int_0^t [1 - F(u)]\, du}{\left(\int_0^t [1 - F(u)]\, du\right)^2} = 0$$

Equation 2 is obtained by setting the nominator equal to 0 as follows:

$$-\left[C_p \cdot [1-F(t)] + C_f \cdot F(t)\right] \cdot [1-F(t)] + \left[-C_p \cdot f(t) + C_f \cdot f(t)\right] \cdot \int_0^t [1-F(u)]\, du = 0$$

***……..Equation 2***

We then reduce Equation 2 to obtain Equation 3:

$$-\left[C_p \cdot [1-F(t)] + C_f \cdot F(t)\right] \cdot [1-F(t)] + \left[-C_p \cdot f(t) + C_f \cdot f(t)\right] \cdot \int_0^t [1-F(u)]\, du = 0$$

$$-C_p[1-F(t)]^2 + C_f \cdot F(t) \cdot [1-F(t)] + \left[-f(t) \cdot \left(C_p - C_f\right)\right] \cdot \int_0^t [1-F(u)]\, du = 0$$

$$\frac{-C_p[1-F(t)]^2 + C_f \cdot F(t) \cdot [1-F(t)] + \left[-f(t) \cdot \left(C_p - C_f\right)\right] \cdot \int_0^t [1-F(u)]\, du}{1-F(t)} = 0$$

$$-C_p \cdot [1-F(t)] - C_f \cdot F(t) + \frac{\left[-f(t) \cdot \left(C_p - C_f\right)\right] \cdot \int_0^t [1-F(u)]\, du}{1-F(t)} = 0$$

$$F(t) \cdot \left(C_p - C_f\right) - C_p + \frac{\left[-f(t) \cdot \left(C_p - C_f\right)\right] \cdot \int_0^t [1-F(u)]\, du}{1-F(t)} = 0$$

$$\frac{F(t) \cdot \left(C_p - C_f\right) - C_p + \frac{\left[-f(t) \cdot \left(C_p - C_f\right)\right] \cdot \int_0^t [1-F(u)] du}{1-F(t)}}{C_p - C_f} = 0$$

$$F(t) - \frac{C_p}{\left(C_p - C_f\right)} - \frac{f(t)}{1-F(t)} \cdot \int_0^t [1-F(u)]\, du = 0 \qquad \textbf{Equation 3}$$

The failure rate function r(t) is defined as r(t) = $\frac{f(t)}{1-F(t)}$ , therefore, Equation 3 can be rewritten as:

$$Equation\ 3\ \rightarrow \boldsymbol{r(t)} \cdot \int_0^t [1-F(u)]\, du - F(t) = \frac{C_p}{\left(C_p - C_f\right)}$$

The probability density function (PDF) and the cumulative distribution function (CDF) of Weibull distribution are as follows:

$$\boldsymbol{PDF} \rightarrow f(t) = \frac{\alpha}{\beta^\alpha} \cdot t^{(\alpha-1)} \cdot e^{-\left(\frac{t}{\beta}\right)^\alpha}$$

$$\boldsymbol{CDF} \rightarrow F(t) = 1 - e^{-\left(\frac{t}{\beta}\right)^\alpha}$$

Then Equation 3 can be written and expanded as follows to obtain Equation 4:

$$Equation\ 3\ \rightarrow \frac{\frac{\alpha}{\beta^{\alpha}}\cdot t^{(\alpha-1)}\cdot e^{-\left(\frac{t}{\beta}\right)^{\alpha}}}{1-\left(1-e^{-\left(\frac{t}{\beta}\right)^{\alpha}}\right)}\cdot\int_{o}^{t} e^{-\left(\frac{u}{\beta}\right)^{\alpha}}du-\left(1-e^{-\left(\frac{t}{\beta}\right)^{\alpha}}\right)=\frac{C_p}{\left(C_p-C_f\right)}$$

$$\boxed{\frac{\alpha}{\beta^{\alpha}}\cdot t^{(\alpha-1)}\cdot\int_{0}^{t} e^{-\left(\frac{u}{\beta}\right)^{\alpha}}du+e^{-\left(\frac{t}{\beta}\right)^{\alpha}}-1=\frac{C_p}{(C_p-C_f)}\qquad \boldsymbol{Equation\ 4}}$$

At this point, Equation 4 will be used to find the value of t that will minimize the cost of the age replacement model. Since it is rather difficult to solve $\int_{o}^{t} e^{-\left(\frac{u}{\beta}\right)^{\alpha}}du$ explicitly, the integral can instead be transformed into a more solvable form. The following example illustrates how the transformation of the integral is done:

Assume the integral $\int_{o}^{t} R(u)\,du$ needs to be evaluated. Where $R(u) = exp\left\{-\left(\frac{u}{\beta}\right)^{\alpha}\right\}$ stands for the reliability function of the Weibull random variable.

Let $y = \left(\frac{u}{\beta}\right)^{\alpha}$ so that $u = \beta \cdot y^{\frac{1}{\alpha}}$ and $= \frac{\beta}{\alpha}\cdot y^{\frac{1}{\alpha}-1}dy$ . The integral can now be written as follows:

$$\int_{0}^{t} R(u)\,du = \int_{0}^{w} e^{-y}\cdot\frac{\beta}{\alpha}\cdot\ y^{\frac{1}{\alpha}-1}dy \qquad where\ w = \left(\frac{t}{\beta}\right)^{\alpha}$$

For Weibull distribution $\int_{o}^{t} R(u)\,du$ can be represented by the incomplete gamma function.

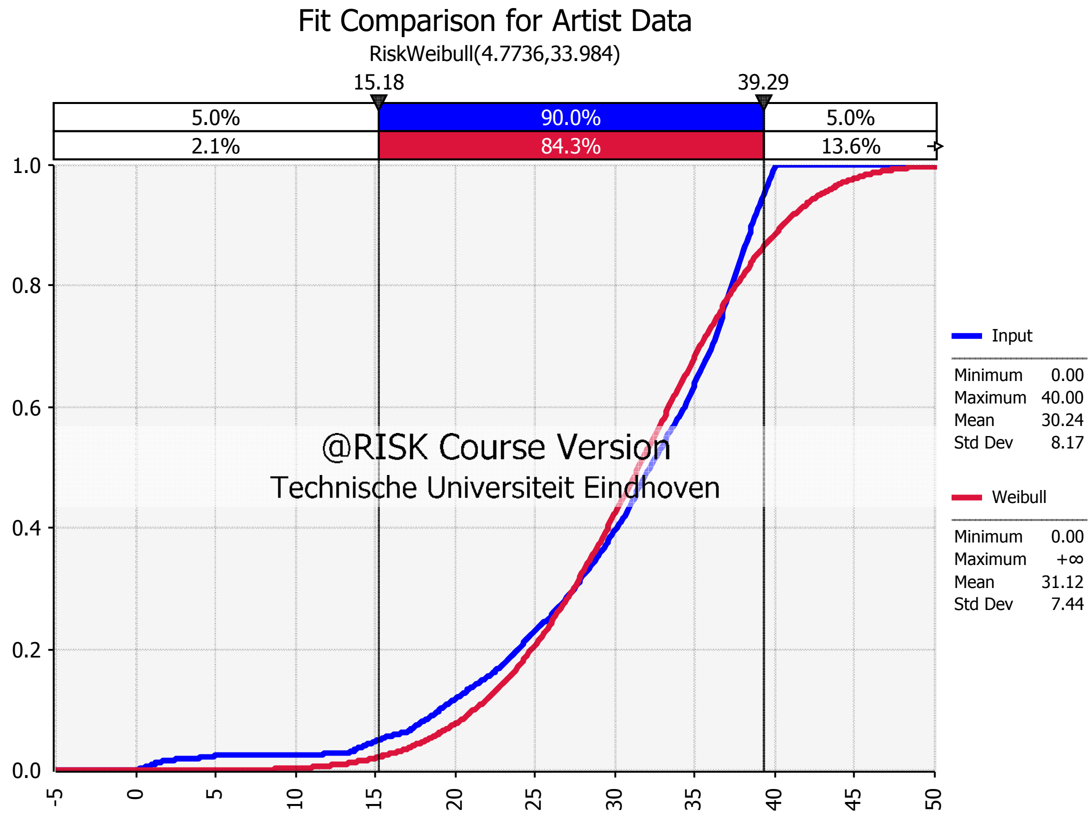
$$\frac{\beta}{\alpha}\cdot\int_{0}^{w} e^{-y}\cdot y^{\frac{1}{\alpha}-1}dy = \frac{\beta}{\alpha}\cdot\Gamma\left(\frac{1}{\alpha},w\right) : Incomplete\ Gamma\ function\ from\ 0\ to\ w$$

Finally, to evaluate this incomplete Gamma function, a built-in command in MATLAB is used. This command is written as **“gammainc( ( t / β ) ^ α, 1/α) * gamma( 1 / α ) * ( β / α )”**. It evaluates the integral form 0 to t.

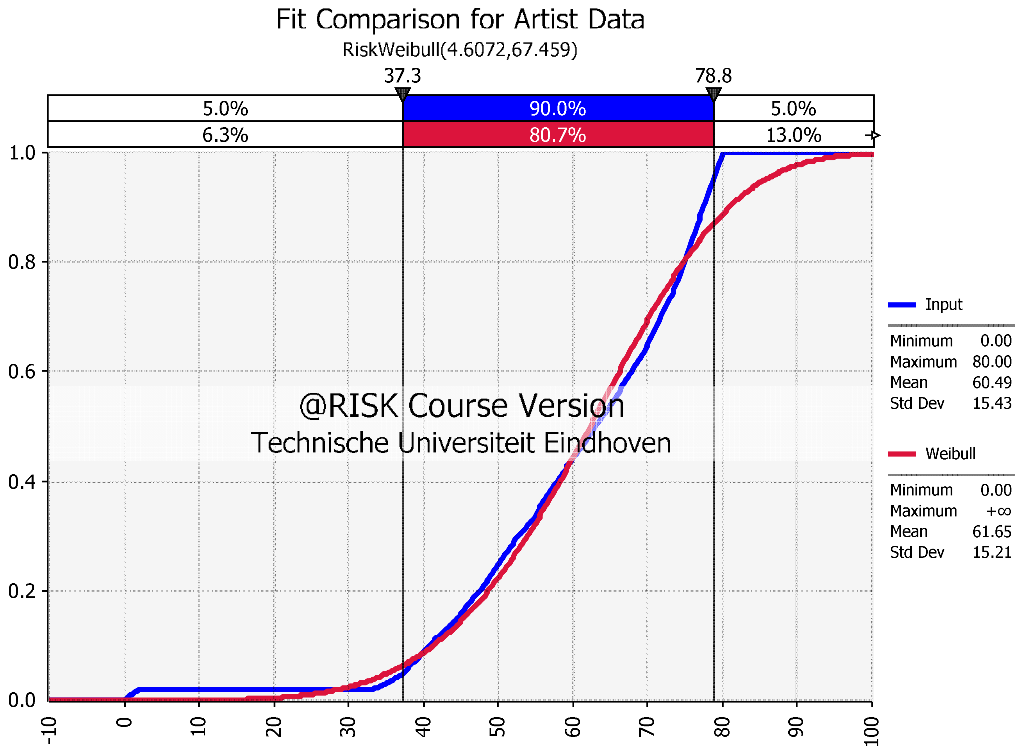
# Appendix D Fitting initial expected life time degradation process.

This Appendix shows the graphical representation of the distribution fitting of the initial cumulative distribution function (CDF) of the failure processes of the assigned critical components. In the project it was assumed that the C – kits of the Chain and Gear Unit have an identical failure behavior considering their CDF. Furthermore, it is assumed that the D – kits Chain and Gear Unit have an identical initial failure process. To estimate the degradation process of the critical components the distribution drawer is used which is provided by @ Risk an Excel add-in program. The blue line is the drawn failure process and the red line indicates the fitted CDF.

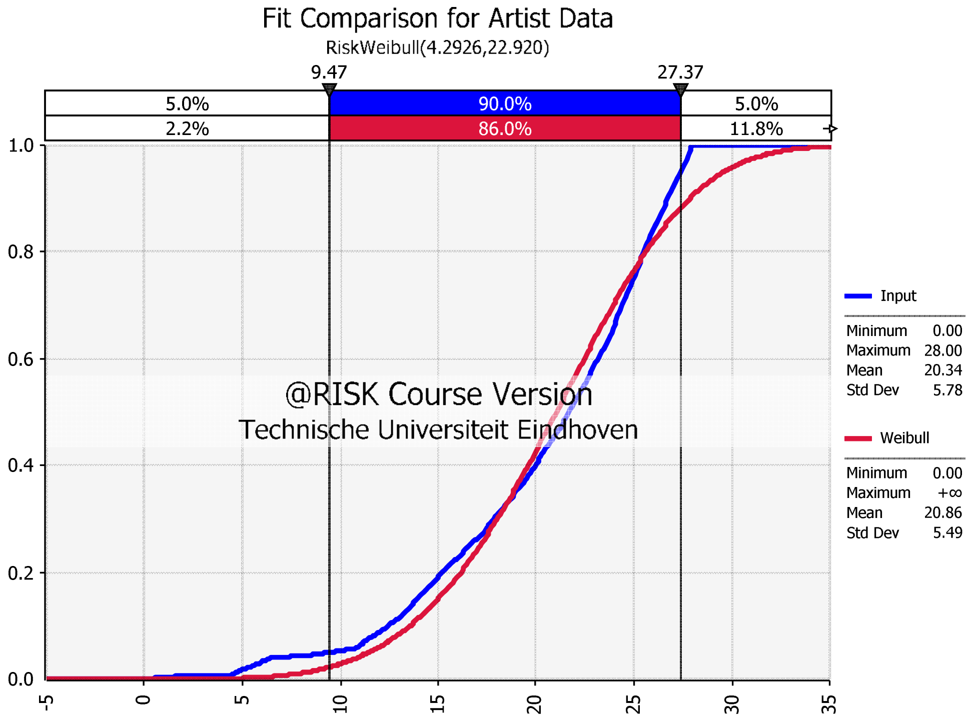
## Fitted distribution for C-Kit Chain and C-Kit Gear Unit



## Fitted distribution for D-Kit Chain and D-Kit Gear Unit



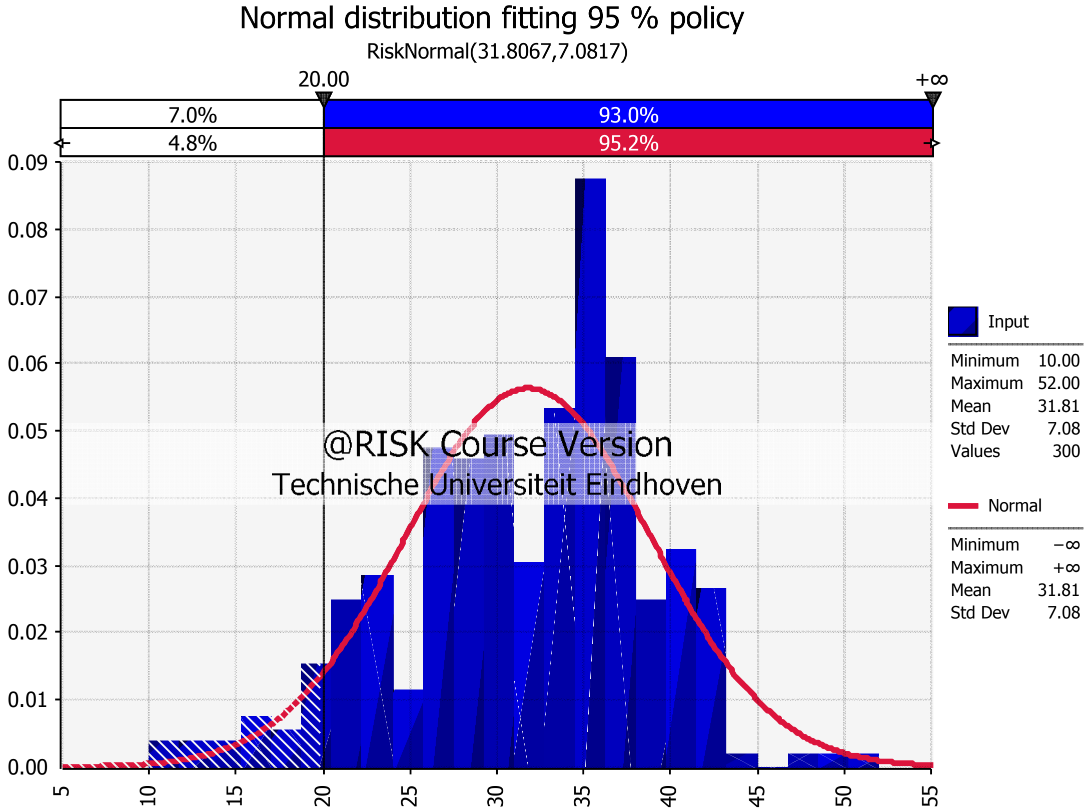
## Fitted distribution for C-Kit Transport



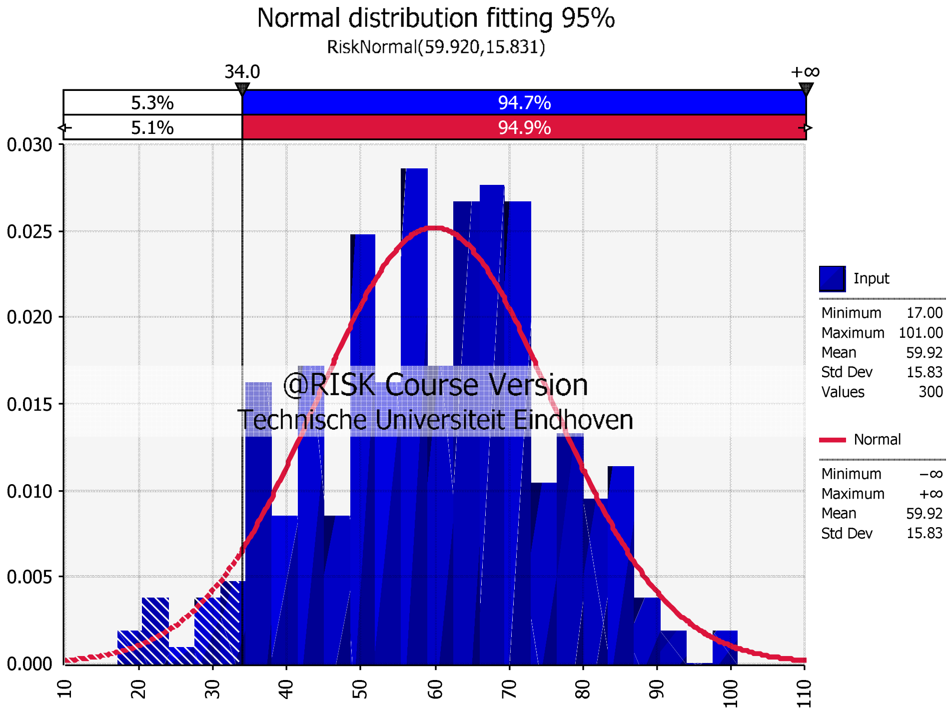
# Appendix E Normal distribution plots 95 % policy: Scenario 1

This Appendix shows the normal distribution plots for the critical components which determined the replacement time interval of the policy. To obtain the data needed to fit a normal distribution a random generation was used. Given the known Weibull distributions with a shape parameter α and a scale parameter β for each component failure times were generated. In the project it was assumed that the C – kits of the Chain and Gear Unit have an identical failure behavior. Furthermore, it is assumed that the D – kits Chain and Gear Unit have an identical initial failure process.

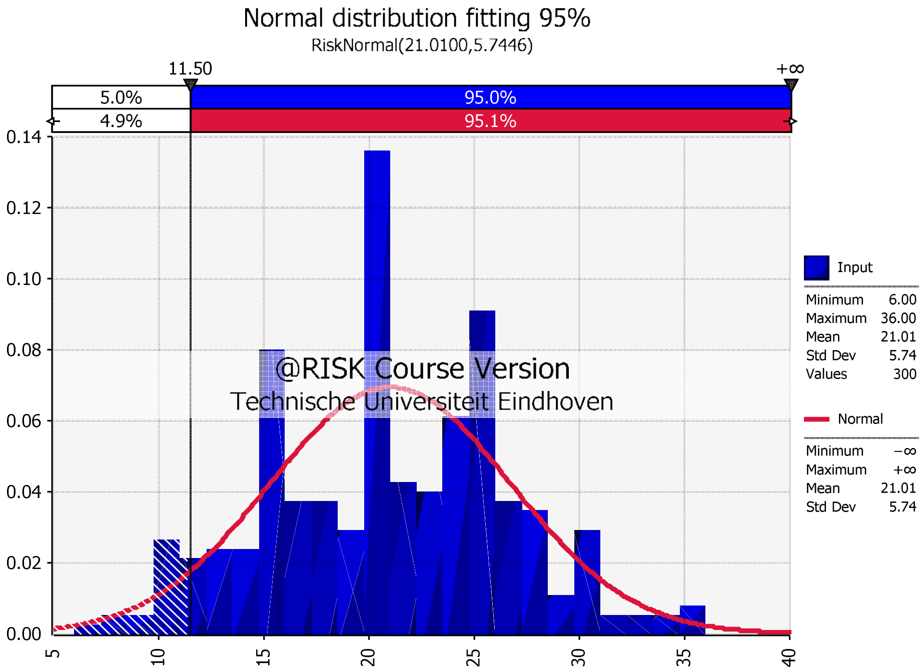
## Normal distribution fitting for C-Kit Chain and C-Kit Gear Unit



## Normal distribution fitting for D-Kit Chain and D-Kit Gear Unit



## Normal distribution fitting for C-Kit Transport



# Appendix F Computation replacement times FCC policy scenario 1

Based on the clustering methodology proposed by Dijkhuizen and van Harten (1997) the clustering policy for scenario 1 has been defined. As explained in Appendix B the policy considers the maintenance kits to be frequency constraint. Hence, each policy must at least be replaced a number of times which is denoted by the parameter $f_i$. This minimum replacement frequency is determined by the individual 95% reliability time interval. The following table shows the parameters used.

| Maintenance Kit | $f_i$ per year | $t_i$ in euros | $\frac{f_i(S+t_i)}{t_i}$ |
|---|---|---|---|
| **14 C indexed i = 1** | 4.4 | 102 | 90.7 |
| **10 C indexed i = 2** | 2.6 | 736 | 9.67 |
| **12 C indexed i = 3** | 2.6 | 842 | 8.7 |
| **10 D indexed i = 4** | 1.6 | 806 | 5.2 |
| **12 D indexed i = 5** | 1.6 | 2578 | 2.84 |

From the last column in the above depicted table we can conclude that it can never be optimal to cluster job 5 with job 1. This because the minimum frequency required for job 1 is larger than the maximum frequency of job 5 shown in the forth column. The proposed algorithm of Dijkhuizen and van Harten (1997) resulted in the following computations.

$$F(1) = min\{f_1 \cdot (S + t_1)\} = min\{4{,}4 \ \cdot (2000 + 102)\} = 9248{,}4$$

$$\begin{aligned} F(2) &= min\{f_1 \cdot (S + t_1 + t_2); F(1) + f_2 \cdot (S + t_2)\} \\ &= min\{4{,}4 \ \cdot (2000 + 102 + 736); F(1) + 2{,}6 \ \cdot (2000 + 736)\} \\ &= 12.487{,}2 \end{aligned}$$

$$\begin{aligned} F(3) &= min\{f_1 \cdot (S + t_1 + t_2 + t_3); F(1) + f_2 \cdot (S + t_2 + t_3); F(2) + f_3 \cdot (S + t_3)\} \\ &= min\{4{,}4 \ \cdot (2000 + 102 + 736 + 842); F(1) + 2{,}6 \ \cdot (2000 + 736 + 842); F(2) \\ &+ 2{,}6 \cdot (2000 + 842)\} \\ &= 16.192 \end{aligned}$$

$$F(4) = min\{f_1 \cdot (S + t_1 + t_2 + t_3 + t_4); F(1) + f_2 \cdot (S + t_2 + t_3 + t_4); F(2) + f_3 \cdot (S + t_3 + t_4); F(3) + f_4 \cdot (S + t_4)\}$$

$$= min\{4{,}4 \cdot (2000 + 102 + 736 + 842 + 806); F(1) + 2{,}6 \cdot (2000 + 736 + 842 + 806); F(2) + 2{,}6 \cdot (2000 + 842 + 806); F(3) + 1{,}6 \cdot (2000 + 806)\}$$

$$= 19.738{,}4$$

$$F(5) = min\{F(1) + f_2 \cdot (S + t_2 + t_3 + t_4 + t_5); F(2) + f_3 \cdot (S + t_3 + t_4 + t_5); F(3) + f_4 \cdot (S + t_4 + t_5); F(4) + f_5 \cdot (S + t_5)\}$$

$$= min\{F(1) + 2{,}6 \cdot (2000 + 736 + 842 + 806 + 2578); F(2) + 2{,}6 \cdot (2000 + 842 + 806 + 2578); F(3) + 1{,}6 \cdot (2000 + 806 + 2578); F(4) + 1{,}6 \cdot (2000 + 2578)\}$$

$$= 24.806{,}4$$

The corresponding policy corresponding to the minimized cost of 24.806,4 euro is;

$$\Omega^* = [\{1, 2, 3\}, \{4, 5\}]$$

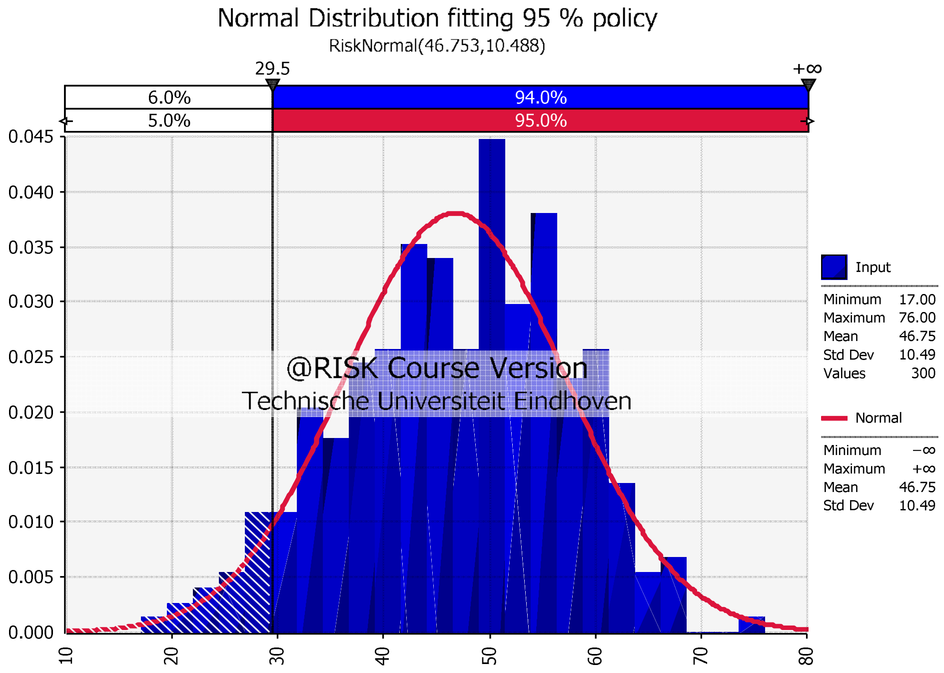
$$= [\{14\ \mathrm{C}, 10\ \mathrm{C}, 12\ \mathrm{C}\}, \{10\ \mathrm{D}, 12\ \mathrm{D}\}]$$

Hence, there are two clusters that must be executed. The first cluster containing three maintenance kits is executed with a frequency of 4,4 times a year which is equal to every 12 weeks whereas the second cluster is executed 1,6 times a year which is equal to every 34 weeks. Therefore the following replacement times have been defined for the 5 maintenance kits which are depicted in the following table.

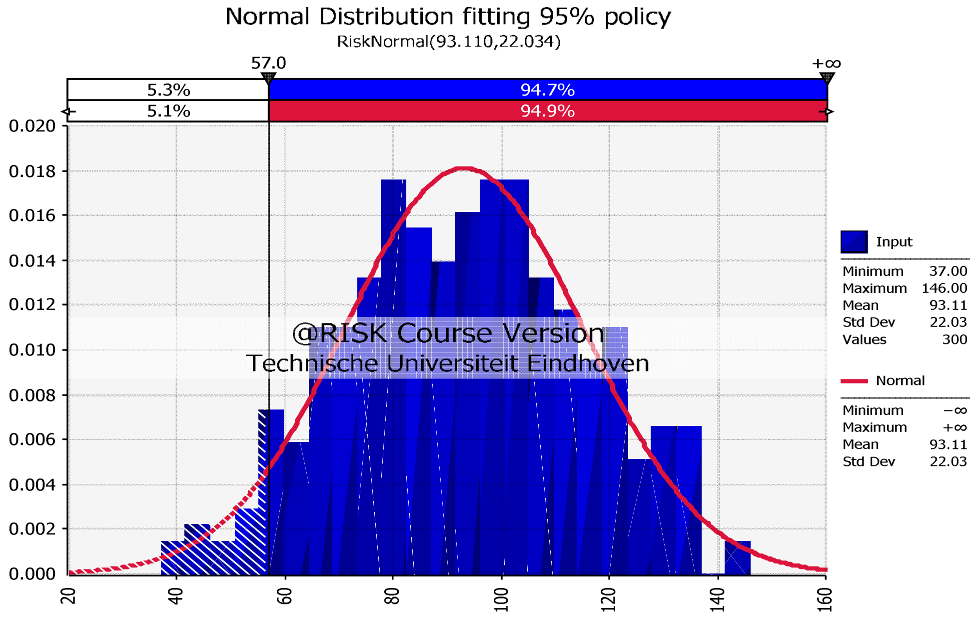
| **Maintenance kit** | **10 C** | **10 D** | **12 C** | **12 D** | **14 C** |
|---|---|---|---|---|---|
| **Replacement interval (weeks)** | 12 | 34 | 12 | 34 | 12 |

# Appendix G Normal distribution plots 95 % policy: Scenario 2

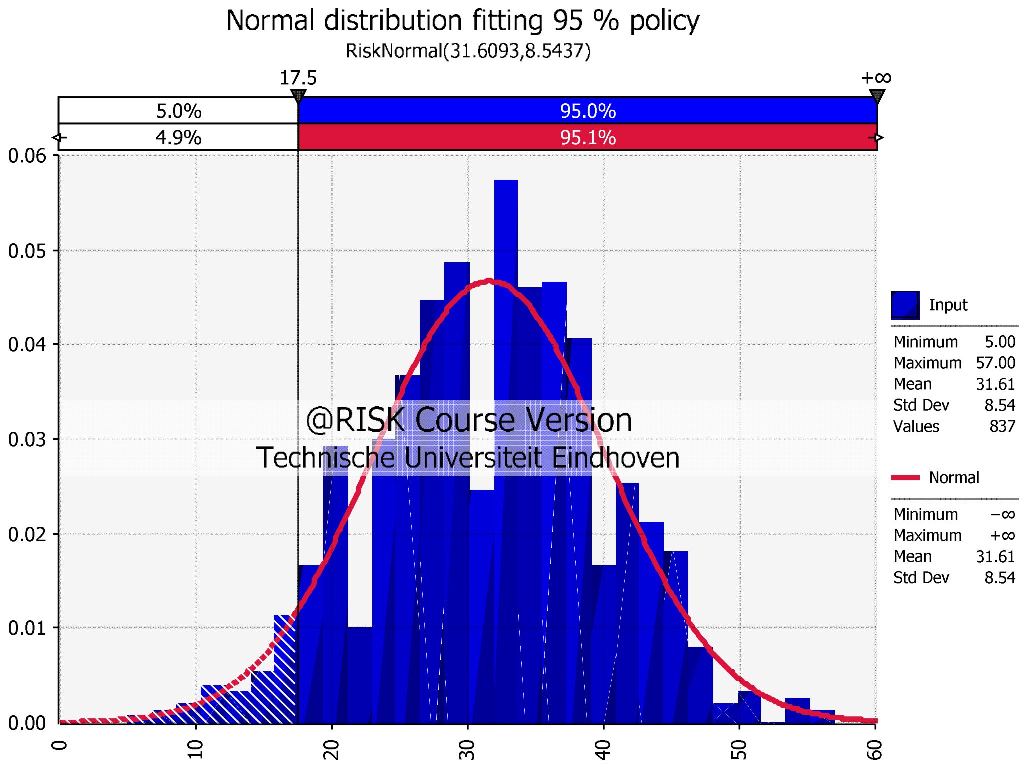
## Normal distribution fitting for C-Kit Chain and C-Kit Gear Unit



## Normal distribution fitting for D-Kit Chain and D-Kit Gear Unit



## Normal distribution fitting for C-Kit Transport



# Appendix H Computation replacement times FCC policy scenario 2

Based on the clustering methodology proposed by Dijkhuizen and van Harten (1997) the clustering policy for scenario 2 has been defined. As explained in Appendix B the policy considers the maintenance kits to be frequency constraint. Hence, each policy must at least be replaced a number of times which is denoted by the parameter $f_i$. This minimum replacement frequency is determined by the individual 95% reliability time interval. The following table shows the parameters used.

| Maintenance Kit | $f_i$ *per year* | $t_i$ *in euros* | $\frac{f_i(S+t_i)}{t_i}$ |
|---|---|---|---|
| **14 C indexed i = 1** | 2.9 | 102 | 80.37 |
| **10 C indexed i = 2** | 1.8 | 736 | 6.69 |
| **12 C indexed i = 3** | 1.8 | 842 | 6.08 |
| **10 D indexed i = 4** | 0.92 | 806 | 3.2 |
| **12 D indexed i = 5** | 0.92 | 2578 | 1.63 |

From the last column in the above depicted table we can conclude that it can never be optimal to cluster job 5 with jobs 1, 2 and 3. This because the minimum frequency required for jobs 1,2 and 3 are larger than the maximum frequency of job 5 shown in the fourth column. Furthermore, Job 4 may not be clustered with Job 1 due to the same reasoning as the above restriction. The proposed algorithm of Dijkhuizen and van Harten (1997) resulted in the following computations.

$$F(1) = min\{f_1 \cdot (S + t_1)\} = min\{2.9 \ \cdot (2000 + 102)\} = 6.095,8$$

$$\begin{aligned} F(2) &= min\{f_1 \cdot (S + t_1 + t_2); F(1) + f_2 \cdot (S + t_2)\} \\ &= min\{2,9 \ \cdot (2000 + 102 + 736); F(1) + 1,8 \ \cdot (2000 + 736)\} \\ &= 8230,2 \end{aligned}$$

$$\begin{aligned} F(3) &= min\{f_1 \cdot (S + t_1 + t_2 + t_3); F(1) + f_2 \cdot (S + t_2 + t_3); F(2) + f_3 \cdot (S + t_3)\} \\ &= min\{2,9 \ \cdot (2000 + 102 + 736 + 842); F(1) + 1,8 \ \cdot (2000 + 736 + 842);\ F(2) \\ &+ 1,8 \ \cdot (2000 + 842)\} \\ &= 10.672 \end{aligned}$$

$$
\begin{aligned}
F(4) &= min\{F(1) + f_2 \cdot (S + t_2 + t_3 + t_4); F(2) + f_3 \cdot (S + t_3 + t_4); F(3) + f_4 \cdot (S + t_4)\} \\
&= min\{F(1) + 1{,}8 \ \cdot (2000 + 736 + 842 + 806); F(2) + 1{,}8 \\
&\cdot (2000 + 842 + 806); F(3) + 0{,}92 \\
&\cdot (2000 + 806)\} \\
&= 13.987
\end{aligned}
$$

$$
\begin{aligned}
F(5) &= min\{; F(3) + f_4 \cdot (S + t_4 + t_5); F(4) + f_5 \cdot (S + t_5)\} \\
&= min\{F(3) + 0{,}92 \cdot (2000 + 806 + 2578); F(4) + 0{,}92 \\
&\cdot (2000 + 2578)\} \\
&= 15.625{,}28
\end{aligned}
$$

The corresponding policy corresponding to the minimized cost of 19.305,28 euro is;

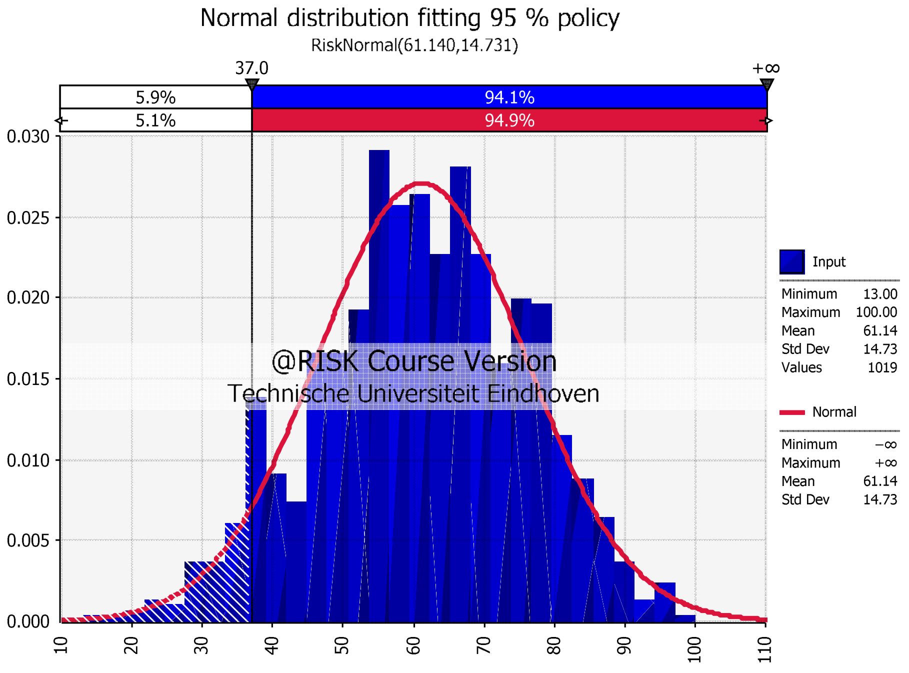
$$
\begin{aligned}
\Omega^* &= [\{1, 2, 3\}, \{4, 5\}] \\
&= [\{14\text{ C}, 10\text{ C}, 12\text{ C}\}, \{10\text{ D}, 12\text{ D}\}]
\end{aligned}
$$

Hence, there are two clusters that must be executed. The first cluster containing three maintenance kits is executed with a frequency of 2,9 times a year which is equal to every 18 weeks whereas the second cluster is executed 0,92 times a year which is equal to every 57 weeks. Therefore the following replacement times have been defined for the 5 maintenance kits which are depicted in the following table.

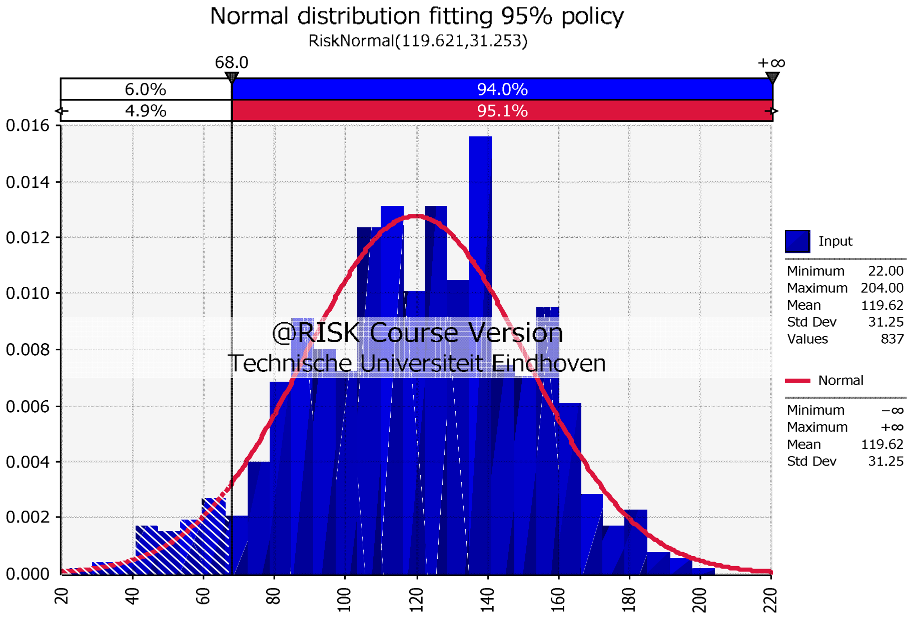
| **Maintenance kit** | **10 C** | **10 D** | **12 C** | **12 D** | **14 C** |
|---|---|---|---|---|---|
| **Replacement interval (weeks)** | 18 | 57 | 18 | 57 | 18 |

# Appendix I Normal distribution plots 95 % policy: Scenario 3

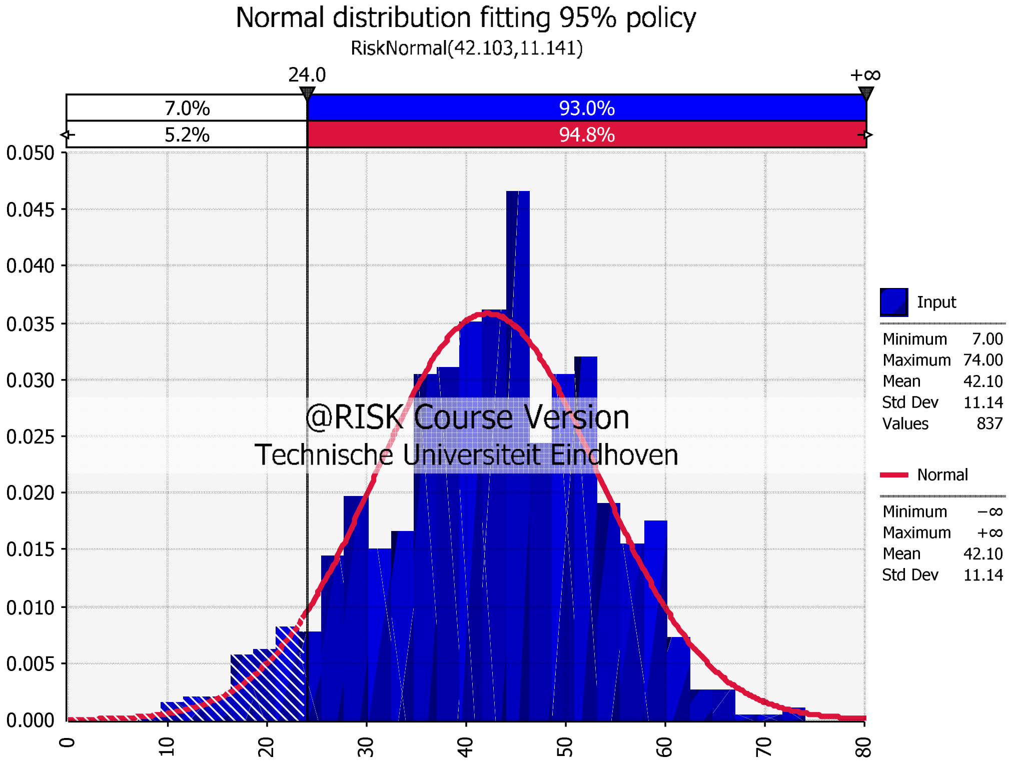
## Normal distribution fitting for C-Kit Chain and C-Kit Gear Unit



## Normal distribution fitting for D-Kit Chain and D-Kit Gear Unit



## Normal distribution fitting for C-Kit Transport



## Appendix J Computation replacement times FCC policy scenario 3

Based on the clustering methodology proposed by Dijkhuizen and van Harten (1997) the clustering policy for scenario 3 has been defined. As explained in Appendix B the policy considers the maintenance kits to be frequency constraint. Hence, each policy must at least be replaced a number of times which is denoted by the parameter $f_i$. This minimum replacement frequency is determined by the individual 95% reliability time interval. The following table shows the parameters used.

| Maintenance Kit | $f_i$ per year | $t_i$ in euros | $\frac{f_i(S+t_i)}{t_i}$ |
|---|---|---|---|
| **14 C indexed i = 1** | 2.2 | 102 | 45.34 |
| **10 C indexed i = 2** | 1.4 | 736 | 5.2 |
| **12 C indexed i = 3** | 1.4 | 842 | 4.73 |
| **10 D indexed i = 4** | 0.8 | 806 | 2.8 |
| **12 D indexed i = 5** | 0.8 | 2578 | 1.42 |

From the last column in the above depicted table we can conclude that it can never be optimal to cluster job 5 with job 1. This because the minimum frequency required for job 1 is larger than the maximum frequency of job 5 shown in the forth column. The proposed algorithm of Dijkhuizen and van Harten (1997) resulted in the following computations.

$$F(1) = min\{f_1 \cdot (S + t_1)\} = min\{2{,}2 \cdot (2000 + 102)\} = 4.624{,}4$$

$$\begin{aligned} F(2) &= min\{f_1 \cdot (S + t_1 + t_2); F(1) + f_2 \cdot (S + t_2)\} \\ &= min\{2{,}2 \cdot (2000 + 102 + 736); F(1) + 1{,}4 \cdot (2000 + 736)\} \\ &= 6.243{,}6 \end{aligned}$$

$$\begin{aligned} F(3) &= min\{f_1 \cdot (S + t_1 + t_2 + t_3); F(1) + f_2 \cdot (S + t_2 + t_3); F(2) + f_3 \cdot (S + t_3)\} \\ &= min\{2{,}2 \cdot (2000 + 102 + 736 + 842); F(1) + 1{,}4 \cdot (2000 + 736 + 842); F(2) \\ &+ 1{,}4 \cdot (2000 + 842)\} \\ &= 8.096 \end{aligned}$$

$$\begin{aligned} F(4) = min\{&f_1 \cdot (S + t_1 + t_2 + t_3 + t_4); F(1) + f_2 \cdot (S + t_2 + t_3 + t_4); F(2) + f_3 \\ &\cdot (S + t_3 + t_4); F(3) + f_4 \cdot (S + t_4)\} \\ &= min\{2{,}2 \ \cdot (2000 + 102 + 736 + 842 + 806); F(1) + 1{,}4 \\ &\cdot (2000 + 736 + 842 + 806); F(2) + 1{,}4 \cdot (2000 + 842 + 806); F(3) + 0{,}8 \\ &\cdot (2000 + 806)\} \\ &= 9.869{,}2 \end{aligned}$$

$$\begin{aligned} F(5) = min\{&F(1) + f_2 \cdot (S + t_2 + t_3 + t_4 + t_5); F(2) + f_3 \cdot (S + t_3 + t_4 + t_5); F(3) + f_4 \\ &\cdot (S + t_4 + t_5); F(4) + f_5 \cdot (S + t_5)\} \\ &= min\{F(1) + 1{,}4 \ \cdot (2000 + 736 + 842 + 806 + 2578); F(2) + 1{,}4 \\ &\cdot (2000 + 842 + 806 + 2578); F(3) + 0{,}8 \cdot (2000 + 806 + 2578); F(4) + 0{,}8 \\ &\cdot (2000 + 2578)\} \\ &= 12.403{,}2 \end{aligned}$$

The corresponding policy corresponding to the minimized cost of 12.403,2 euro is;

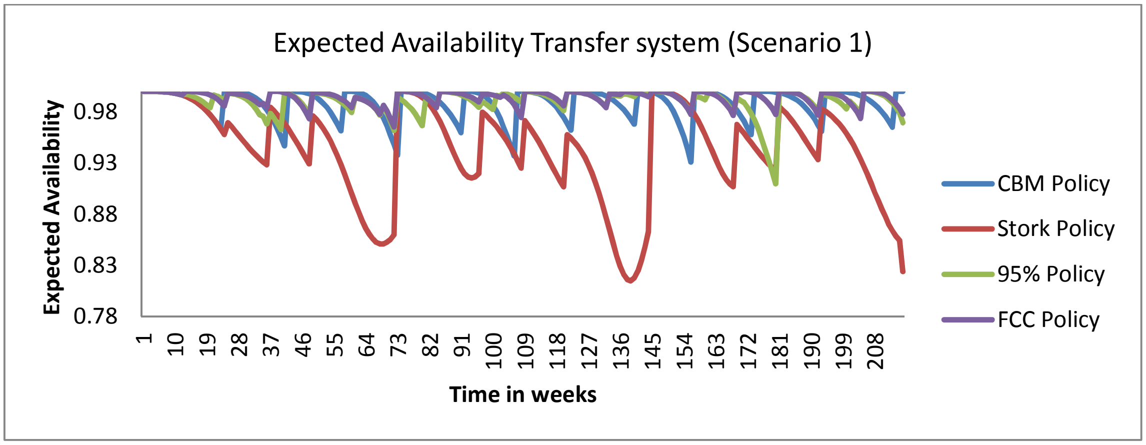
$$\Omega^* = [\{1, 2, 3\}, \{4, 5\}]$$

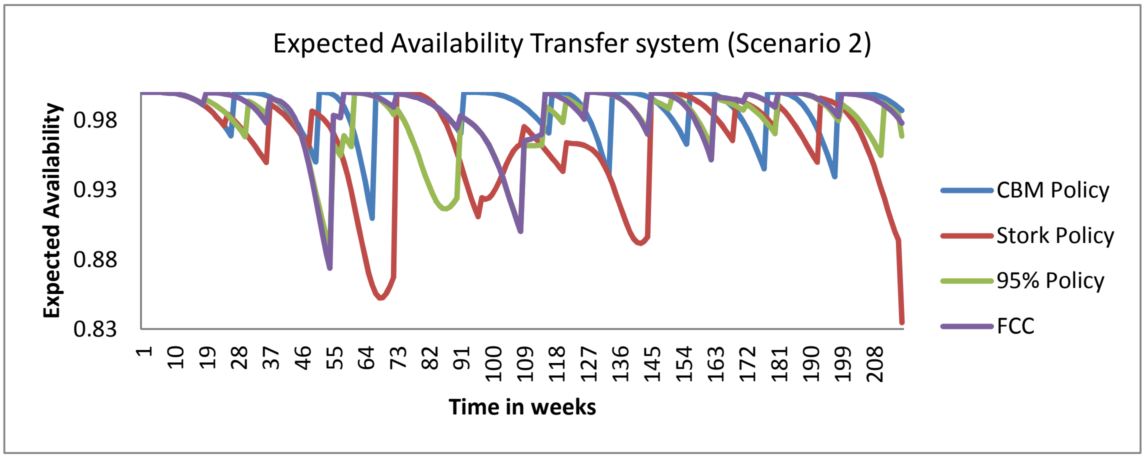
$$= [\{14\ \mathrm{C}, 10\ \mathrm{C}, 12\ \mathrm{C}\}, \{10\ \mathrm{D}, 12\ \mathrm{D}\}]$$

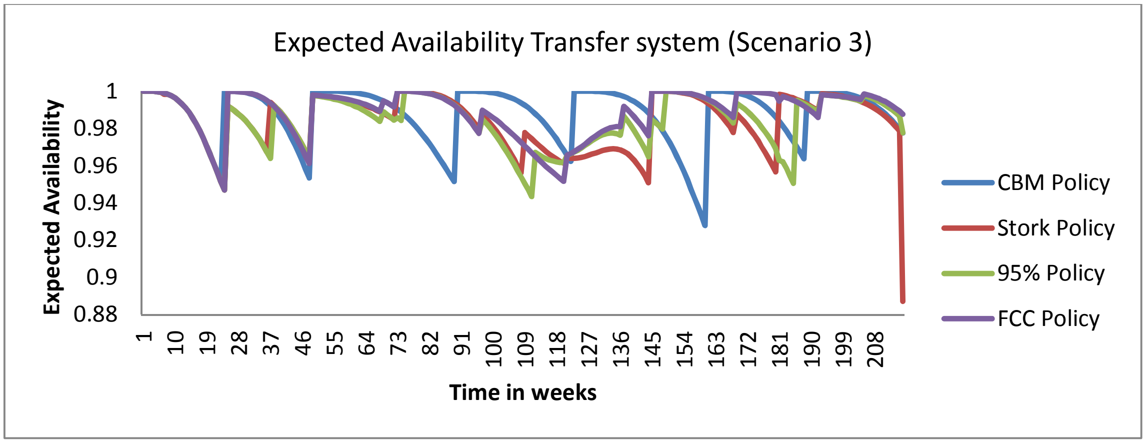
Hence, there are two clusters that must be executed. The first cluster containing three maintenance kits is executed with a frequency of 2,2 times a year which is equal to every 24 weeks whereas the second cluster is executed 0,8 times a year which is equal to every 68 weeks. Therefore the following replacement times have been defined for the 5 maintenance kits which are depicted in the following table.

| **Maintenance kit** | **10 C** | **10 D** | **12 C** | **12 D** | **14 C** |
|---|---|---|---|---|---|
| **Replacement interval (weeks)** | 24 | 68 | 24 | 68 | 24 |

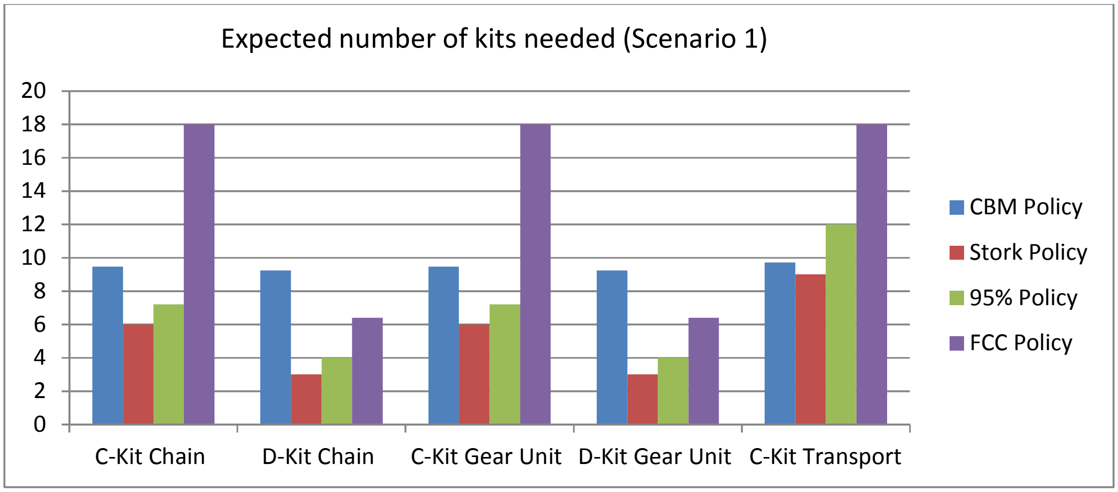
# Appendix K Performance measure Expected Availability

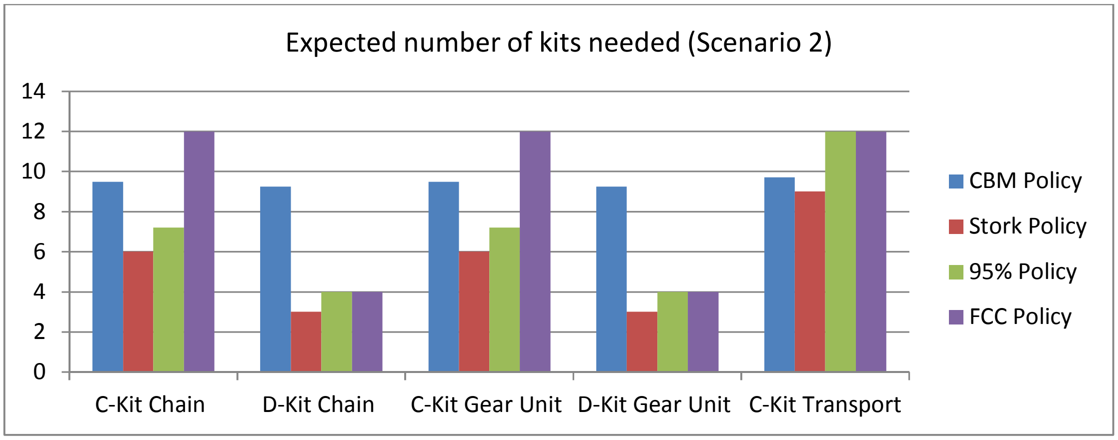


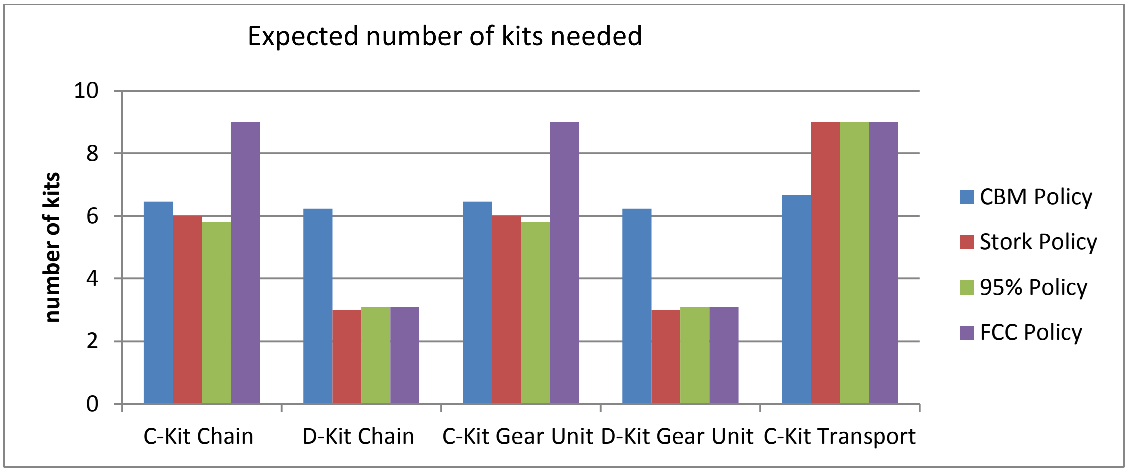




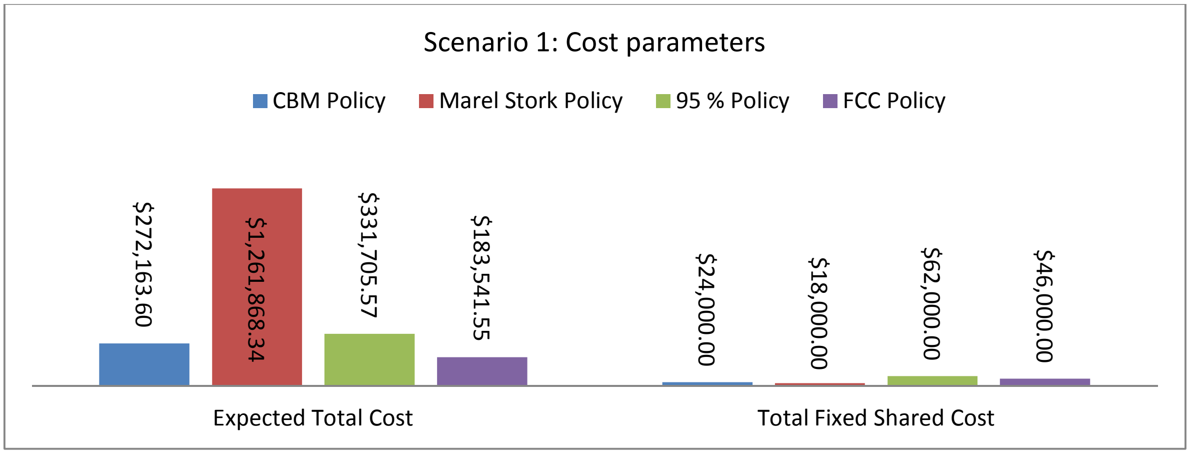
# Appendix L Performance measure Expected number of kits replaced

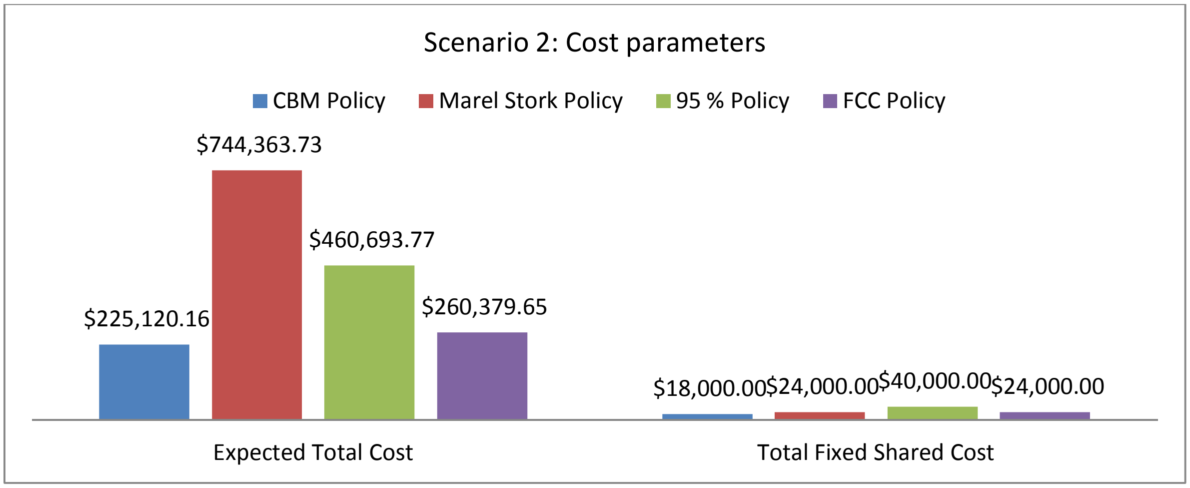


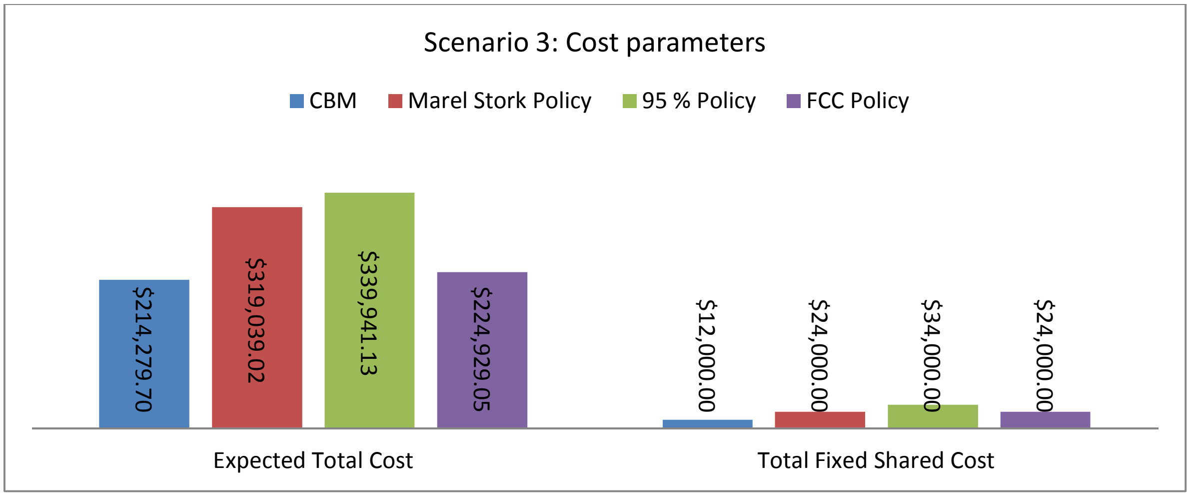




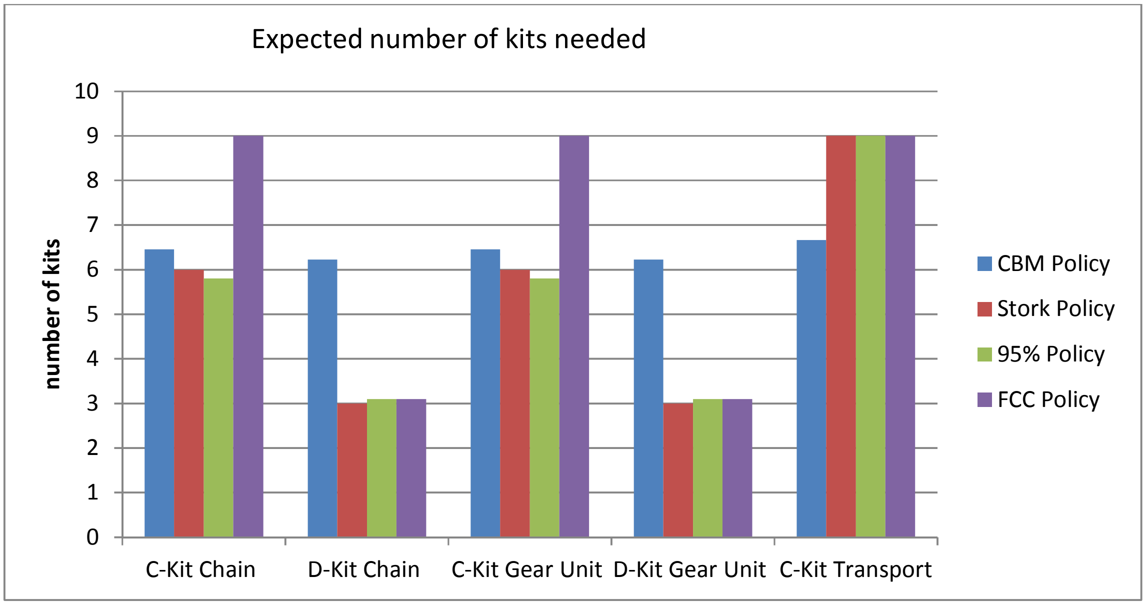
## Appendix M Performance measure Expected Total Cost







# Appendix O Number of kits replaced: 95 % reliability failure threshold – low corrective maintenance costs



## Appendix P Computation replacement times FCC policy High Fixed Costs

Based on the clustering methodology proposed by Dijkhuizen and van Harten (1997) the clustering policy for scenario 3 with high shared fixed costs has been defined. As explained in Appendix B the policy considers the maintenance kits to be frequency constraint. Hence, each policy must at least be replaced a number of times which is denoted by the parameter $f_i$. This minimum replacement frequency is determined by the individual 95% reliability time interval. The following table shows the parameters used.

| Maintenance Kit | $f_i$ *per year* | $t_i$ *in euros* | $\frac{f_i(S+t_i)}{t_i}$ |
|---|---|---|---|
| **14 C indexed i = 1** | 2.2 | 102 | 433,57 |
| **10 C indexed i = 2** | 1.4 | 736 | 39,44 |
| **12 C indexed i = 3** | 1.4 | 842 | 34,65 |
| **10 D indexed i = 4** | 0.8 | 806 | 20,65 |
| **12 D indexed i = 5** | 0.8 | 2578 | 7 |

From the last column in the above depicted table we can conclude that there are no prior clusterinf constraints. The proposed algorithm of Dijkhuizen and van Harten (1997) resulted in the following computations.

$$F(1) = min\{f_1 \cdot (S + t_1)\} = min\{2{,}2\ \cdot (20.000 + 102)\} = 44.224{,}4$$

$$\begin{aligned} F(2) = min\{f_1 \cdot (S + t_1 + t_2); F(1) + f_2 \cdot (S + t_2)\} \\ = min\{2{,}2\ \cdot (20.000 + 102 + 736); F(1) + 1{,}4\ \cdot (20.000 + 736)\} \\ = 45.843{,}6 \end{aligned}$$

$$F(3) = min\{f_1 \cdot (S + t_1 + t_2 + t_3); F(1) + f_2 \cdot (S + t_2 + t_3); F(2) + f_3 \cdot (S + t_3)\}$$

$$= min\{2{,}2 \ \cdot (20.000 + 102 + 736 + 842); F(1) + 1{,}4$$

$$\cdot (20.000 + 736 + 842); F(2) + 1{,}4$$

$$\cdot (20.000 + 842)\}$$

$$= 47.696$$

$$F(4) = min\{f_1 \cdot (S + t_1 + t_2 + t_3 + t_4); F(1) + f_2 \cdot (S + t_2 + t_3 + t_4); F(2) + f_3$$

$$\cdot (S + t_3 + t_4); F(3) + f_4 \cdot (S + t_4)\}$$

$$= min\{2{,}2 \ \cdot (20.000 + 102 + 736 + 842 + 806); F(1) + 1{,}4$$

$$\cdot (20.000 + 736 + 842 + 806); F(2) + 1{,}4 \cdot (20.000 + 842 + 806); F(3) + 0{,}8$$

$$\cdot (20.000 + 806)\}$$

$$= 49.469{,}2$$

$$F(5) = min\{f_1 \cdot (S + t_1 + t_2 + t_3 + t_4 + t_5);\ F(1) + f_2 \cdot (S + t_2 + t_3 + t_4 + t_5); F(2) + f_3$$

$$\cdot (S + t_3 + t_4 + t_5); F(3) + f_4 \cdot (S + t_4 + t_5); F(4) + f_5 \cdot (S + t_5)\}$$

$$= min\{2.2 \cdot (20.000 + 102 + 736 + 842 + 806 + 2574); F(1) + 1{,}4$$

$$\cdot (20.000 + 736 + 842 + 806 + 2578); F(2) + 1{,}4$$

$$\cdot (20.000 + 842 + 806 + 2578); F(3) + 0{,}8 \cdot (20.000 + 806 + 2578); F(4) + 0{,}8$$

$$\cdot (20.000 + 2578)\}$$

$$= 55.132$$

The corresponding policy corresponding to the minimized cost of 12.403,2 euro is;

$$\Omega^* = [\{1, 2, 3, 4, 5\}]$$

$$= [\{14\text{ C}, 10\text{ C}, 12\text{ C}, 10\text{ D}, 12\text{ D}\}]$$

Hence, there is one cluster that must be executed. The first and only cluster containing is executed with a frequency of 2,2 times a year which is equal to every 24. Therefore the following replacement times have been defined for the 5 maintenance kits which are depicted in the following table.

| **Maintenance kit** | **10 C** | **10 D** | **12 C** | **12 D** | **14 C** |
|---|---|---|---|---|---|
| **Replacement interval (weeks)** | 24 | 24 | 24 | 24 | 24 |

# Appendix Q Performance measures scenario: high Shared Fixed Costs